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Effect of foliar application of Nano-Micronutrients on growth, and quality parameters of Parthenocarp Cucumber (*Cucumis sativus* L.)

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Abstract

The present investigation was conducted to study the effect of foliar application of Nano-Zinc Oxide (Nano-ZnO) and Nano-Silicon Dioxide (Nano-SiO₂) on growth and quality parameters of parthenocarpic cucumber (*Cucumis sativus* L.) under polyhouse condition. Sixteen treatment combinations comprising four levels of Nano-ZnO (0, 300, 400, and 500 ppm) and four levels of Nano-SiO₂ (0, 200, 400, and 600 ppm) were evaluated in a Factorial Randomized Block Design with three replications. The results revealed significant improvements in growth and quality attributes. For vine length, the maximum at 30 and 60 DAS was recorded in T₃ (0 ppm ZnO + 600 ppm SiO₂) with 44.70 cm and 219.52 cm, respectively, while at 45 DAS, T₁₂ (500 ppm ZnO + 0 ppm SiO₂) recorded the maximum (122.34 cm). T₁₁ (400 ppm ZnO + 600 ppm SiO₂) consistently recorded the maximum number of leaves per plant (14.13, 25.20, and 34.87 at 30, 45, and 60 DAS). T₃ recorded the maximum number of branches (4.87, 9.00, and 13.20) and Leaf Area Index (98.60, 198.53, and 249.07) across all stages. Regarding quality parameters, T₃ recorded the maximum TSS (5.113 °Brix), pH (6.41), and fruit firmness (5.86), while T₁₅ (500 ppm ZnO + 600 ppm SiO₂) recorded the lowest physiological loss of weight (4.027%) indicating best shelf life. The treatment T₁₅ exhibited severe antagonistic effects on growth parameters and should be strictly avoided. In conclusion, for maximizing growth and quality, T₃ (0 ppm ZnO + 600 ppm SiO₂) is recommended for parthenocarpic cucumber cultivation under polyhouse conditions.

Keywords: Parthenocarpic cucumber, Nano-ZnO, Nano-SiO₂, growth, yield, quality, foliar application

1. Introduction

The Vegetables are a group of plants that are edible and are a vital part of human nutrition. The vegetable kingdom comprised of a large number of plants, mostly annuals, of different parts like stem, flower bud, fruit, root etc. are consumed by humans and animals. Vegetables provide all the nutrients and contain abundance of vitamins and minerals and Fiber which are rightly called as protective foods.

Vegetables are grown in 204.83 million metric tonnes from an area of 11.35 million ha (2022-23, 3rd Estm). according to FaO (2021), and 13.1% of India's cropped area is used for vegetable cultivation, with India being the second largest producer of vegetables globally next only to China, contributing significantly to the horticulture sector which accounts for around 33% of the agricultural Gross Value Added (GVA).

The Cucumber (*Cucumis sativus* L.) a member of the Cucurbitaceae family, has a diploid chromosome number of 2n = 2X=14. Cucumbers are native to the Himalayan foothills of northern India and Nepal. They were domesticated at least 5,000 years ago. It is believed to be originated in India and the wild relative *Cucumis sativus* var. *hardwickii* is the progenitor of the cultivated cucumber (Choudhary *et al.* 2015; Kaur and Sharma 2021) [4, 10].

Parthenocarpic cucumbers are seedless or nearly seedless cucumbers that develop without pollination. They are a type of cucumber that produce female-only flowers. Cucumber is commonly a monoecious annual having all sex forms such as androecious, gynoecious, hermaphrodite, and andromonoecious.

It is most suitable vegetable for protected conditions due to year-round production and higher demand in market. Due to its origin in India, it has accumulated most of the genetic variability which helps to improve various characters through

selection. Germplasm purity is difficult to maintain due to higher cross pollination in cucumber. It depicts wide range of variability with no uniformity in characters like fruit size, shape, color and yield among existing germplasm (Sharma *et al.* 2017) [24].

Parthenocarp and gynoeceious genotypes are widely grown under protected conditions which, bear female flowers in every node and develop seedless fruits. Presence of genetic variability in germplasm helps in crop improvement through selection. Protected cultivation is the most efficient way to overcome various biotic and abiotic stresses, useful for offseason vegetable cultivation, cultivation of parthenocarp cucumber under protected cultivation has brought revolution.

Among essential micronutrients, Zinc (Zn) plays a pivotal role in cucumber productivity. It is a vital cofactor for numerous enzymes involved in critical metabolic pathways, including auxin (IAA) synthesis, protein formation, and carbohydrate metabolism. Zinc deficiency disrupts these processes, manifesting as stunted growth, chlorosis, and reduced fruit set and development. Similarly, *Silicon* (Si), though not considered essential for all plants, is a beneficial element that confers significant advantages to cucurbits like cucumber. *Silicon* deposition in epidermal cells enhances mechanical strength, improves biotic and abiotic stress resistance (against pests, diseases, and environmental stress), and promotes photosynthetic efficiency by maintaining erect leaf posture. The combined action of Zn and Si can, therefore, address both the metabolic and structural needs of a high-yielding parthenocarpic crop.

Conventional soil and foliar application of micronutrients face considerable challenges, including low nutrient-use efficiency due to fixation in the soil, leaching, poor uptake, and uneven distribution within plant tissues. This is where nanotechnology offers a revolutionary approach in agricultural nutrient management. Nano-fertilizers, engineered particles typically between 1- 100 nanometers, exhibit unique physicochemical properties such as a high surface area-to-volume ratio, enhanced solubility, and the ability to penetrate plant surfaces (via stomata, cuticle, or ectodesmata) more efficiently. Zinc oxide nanoparticles (ZnO-NPs) and *Silicon* dioxide nanoparticles (SiO₂-NPS) represent promising carriers for delivering Zn and Si in a more bioavailable form. Their small size facilitates easier absorption and translocation within the plant, potentially allowing for lower doses, reduced environmental loss, and targeted physiological effects compared to their bulk or salt counterparts.

Nano-zinc (Zn)

Can boost plant defense mechanisms, improve fruit quality, and promote root development. Use of nanozinc shows significantly increase cucumber production by improving plant growth, fruit size and yield primarily due to the enhanced nutrient uptake and improved resistance to stress conditions like drought resulting in better quality fruits.

Nano-silicon (Si): May enhance plant growth, increasing stress tolerance, increase plant biomass as nano-silicon can promote better vegetative growth, leading to large leaf area and increase plant biomass, increase photosynthetic activity as nano-silicon can increase chlorophyll content, leading to enhance photosynthesis and boosting yield. Nano- silicon can facilitate the uptake of essential nutrients from the soil, improving nutrient use efficiency and also strengthened plant tissues due to which it can provide resistance to certain plant diseases.

2. Materials and Methods: The present investigation entitled “Effect of foliar application of Nano - Micronutrients on growth, yield, and quality parameters of Parthenocarp Cucumber (*Cucumis sativus* L.) was undertaken at Vegetable Research Farm, Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology & Sciences, Prayagraj (UP) during 2025. The experiment was carried out to study the growth parameter, yield and quality attribute of Parthenocarp Cucumber under polyhouse condition at different concentration of zinc oxide and silicon dioxide and their combinations. Details are mentioned in this chapter regarding the materials used and the techniques used throughout the course of investigation.

The experiment was conducted at Vegetable Research Farm, Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology & Sciences, Prayagraj (U.P.), India – 211007, during 2025. All the facilities necessary for cultivation, including labor were made available in the department. The experimental site is located at 24.26 N latitude 81.51 E longitude and 98m above the mean sea level. Prayagraj is located in the south-east part of Uttar Pradesh India. Prayagraj falls under agroclimatic zone IV which is named as “ middle Gangetic plains” the site of experiment is located at 25.57° N latitude 81.51° E longitude and 98 meter above the sea level, the temperature falls down as low as 4-5° during winter the average rainfall in this area is around during winter season especially in the month of December and January the average rainfall in this area is around 103.4 mm annually with maximum concentration during July to September with few showers and drizzles in winter also. The area of Allahabad district comes under subtropical belt in the South east of Uttar Pradesh, which experience extremely hot summer and fairly cold winter. The major part of rain is received from mid-July to September. The winter season starts from November and continues up to the first week of March with mean temperature ranging from 15-25 °C.

The hot season prevails from April to June and May normally being the hottest month of the year. The temperature during summer is intense and recorded a little below 45 °C; relative humidity during summer varies from 20 to 95 per cent.

The experiment is to be laid out in a Factorial Randomized Block Design with 16 treatments (15 treatments + 1 Control) and three replications. The treatment consists of different nano micronutrients at different concentration.

Table 1: Different levels of Nanom micronutrients (ZnO, SiO₂) at different concentration:

Sr. No.	Treatment	Treatment Combination
1	T ₀	NPs.ZnO(0ppm)+ NPs.SiO ₂ (0ppm) (control)
2	T ₁	NPs.ZnO(0ppm)+ NPs.SiO ₂ (200ppm)
3	T ₂	NPs.ZnO(0ppm)+ NPs.SiO ₂ (400ppm)
4	T ₃	NPs.ZnO(0ppm)+ NPs.SiO ₂ (600ppm)

5	T ₄	NPs.ZnO(300ppm)+ NPs.SiO ₂ (0ppm)
6	T ₅	NPs.ZnO(300ppm)+ NPs.SiO ₂ (200ppm)
7	T ₆	NPs.ZnO(300ppm)+ NPs.SiO ₂ (400ppm)
8	T ₇	NPs.ZnO(300ppm)+ NPs.SiO ₂ (600ppm)
9	T ₈	NPs.ZnO(400ppm)+ NPs.SiO ₂ (0ppm)
10	T ₉	NPs.ZnO(400ppm)+ NPs.SiO ₂ (200ppm)
11	T ₁₀	NPs.ZnO(400ppm)+ NPs.SiO ₂ (400ppm)
12	T ₁₁	NPs.ZnO(400ppm)+NPs.SiO ₂ (600ppm)
13	T ₁₂	NPs.ZnO(500ppm)+NPs.SiO ₂ (0ppm)
14	T ₁₃	NPs.ZnO(500ppm)+NPs.SiO ₂ (200ppm)
15	T ₁₄	NPs.ZnO(500ppm)+NPs.SiO ₂ (400ppm)
16	T ₁₅	NPs.ZnO(500ppm)+NPs.SiO ₂ (600ppm)

3. Results and Discussion

3.1 Growth Parameters

3.1.1 Vine Length (cm)

Table 2 presents notable variation in Vine length varied significantly across growth stages. At 30 DAS, the maximum (44.70 cm) was recorded in T₃ (0. ppm ZnO + 600 ppm SiO₂), followed by T₅ (42.54 cm), while the minimum (23.63 cm) was in T₀ (Control). At 45 DAS, the maximum shifted to T₁₂ (500 ppm ZnO+0 ppm SiO₂) with 122.34 cm, followed by T₅ (119.02 cm), with the minimum in T₀ (56.64 cm). At 60 DAS, the maximum returned to T₃ with 219.52 cm, followed by T₅ (217.92: cm), while the minimum was in T₀ (198.51 cm). A strong antagonistic effect was observed in T₁₅ (500 ppm ZnO + 600 ppm SiO₂), which recorded only 59.56 cm at 45 DAS. The significant increase in vine length with Nano-ZnO application up to 400 ppm demonstrates zinc's essential role as a cofactor for tryptophan synthase in IAA biosynthesis, promoting cell elongation and internode expansion (Cakmak *et al.*, 1989; Marschner, 2012) [3, 19]. Similar findings were reported by Mahajan *et al.* (2011) [18] who observed increased root and shoot growth in mung bean and chickpea with ZnO nanoparticles at optimal concentrations. The decline at 500 ppm indicates zinc toxicity, consistent with Yang *et al.* (2015) who reported inhibited root elongation in maize and rice at 2000 mg L⁻¹ ZnO NPs. Nano · SiO₂ enhanced vine length through silica deposition in cell walls, improving mechanical strength and nutrient uptake (Epstein, 1999; Savvas *et al.*, 2009) [6, 23]. Khademi *et al.* (2022) [11] also reported increased fruit yield and plant growth with Si NPs application in cucumber cultivars. The shift in optimal treatment from T₃ (silicon alone) at 30 and 60 DAS to T₁₂ (zinc alone) at 45 DAS suggests temporal variation in nutrient demand. The synergistic effect in T₅ (300 ppm ZnO + 200 ppm SiO₂) aligns with Sen Li *et al.* (2020) [14] who reported that foliar spraying with ZnO-NPs and SiO₂-NPs improved cucumber plant performance. The antagonistic effect in T₁₅ (500 ppm ZnO + 600 ppm SiO₂) confirms competitive inhibition through shared transport pathways (Ma *et al.*, 2007; Ma & Yamaji, 2006) [17, 16].

3.1.2. Number of Leaves per Plant

Table 2 presents notable variation in the maximum number of leaves at 30, 45, and 60 DAS was consistently recorded in T₁₁ (400 ppm ZnO+600 ppm SiO₂) with 14.13, 25.20, and 34.87 leaves, respectively, followed by T₈ (13.33, 22.20, and 32.40 leaves). The minimum at all stages was in T₀ (Control) with 6.93, 12.93, and 19.40 leaves, respectively. The increase in leaf number with Nano-ZnO up to 400 ppm is attributed to zinc's role in protein synthesis, auxin metabolism, and cell division (Marschner, 2012) [19]. Nithya *et al.* (2018) [21] observed significantly higher leaf number in

mulberry with foliar application of nano zinc oxide @ 50 ppm. Kumar *et al.* (2017) [13] also reported increased leaf number in strawberry with nano zinc oxide @ 150 ppm. The decline at 500 ppm indicates toxicity, consistent with Ammoaghaie *et al.* (2016) [2] who reported decreased growth traits at higher nanoparticle concentrations. Nano · SiO₂ showed less pronounced effects on leaf number, playing a secondary role. T₁₁ (400 ppm ZnO+600 ppm SiO₂) consistently produced maximum leaves across all stages, demonstrating strong synergy where silicon enhances zinc utilization and reduces oxidative stress (Neumann & zur Nieden, 2001) [20]. Sen Li *et al.* (2020) [14] confirmed that ZnO-NPs and SiO₂ – NPs improved chlorophyll contents and fresh/dry weights of leaves and roots in cucumber. Increased leaf number provides greater photosynthetic area for assimilate production and improved canopy development (Kumar *et al.*, 2016) [12].

3.1.3 Number of Branches per Plant

Table 2 presents notable variation that in *Silicon* played a dominant role in branching. The maximum branches at 30, 45, and 60 DAS was recorded in T₃ (0. ppm ZnO+600 ppm SiO₂) with 4.87, 9.00, and 13.20 branches, respectively, followed by T₅ (4.07 and 8.40 branches at 30 and 45 DAS) and T₄ / T₁₂ (12.27 branches at 60 DAS). The minimum was in T₀ with 1.80, 3.60, and 7.60 branches, respectively. T₁₅ (500 ppm ZnO+600 ppm SiO₂) showed severe antagonism with only 7.80 branches at 60 DAS. Branching showed silicon playing a dominant role, with T₃ (0 ppm ZnO+600ppmSiO₂) recording maximum branches across all stages. The control produced highest branches among zinc concentrations at 30 DAS, indicating that zinc promotes apical dominance through auxin synthesis (Cakmak *et al.*, 1989; Marschner, 2012) [3, 19]. *Silicon* promotes branching by enhancing cell wall strength, improving nutrient distribution, and balancing hormonal signals (Epstein, 1999; Liang *et al.*, 2007) [6, 15]. Similar results were reported by Gustavo *et al.* (2020) who observed improved fruit quality parameters with Si application in cucumber. The synergistic effect in T₅ (300 ppm ZnO+200 ppm SiO₂) and antagonistic effect in T₁₅ confirm that high zinc strengthens apical dominance. Increased branching provides additional fruiting nodes and improves light distribution (Kumar *et al.*, 2016) [12].

3.1.4. Leaf Area Index (LAI)

Table 2 presents notable variation in the maximum LAI at 30, 45, and 60 DAS was recorded in T₃ (0 ppm ZnO+600 ppm SiO₂) with 98.60, 198.53, and 249.07, respectively, followed by T₅ (96.93, 195.13, and 247.07). The minimum was in T₀ with 44.07, 92.33, and 160.47, respectively. T₁₅ recorded a very low LAI of 160.87 at 60 DAS, nearly equal

to the control. The increase in LAI with Nano-ZnO up to 400 ppm demonstrates zinc's role in leaf expansion through auxin synthesis and carbonic anhydrase activity (Cakmak *et al.*, 1989; Marschner, 2012) [3, 19]. Poornima *et al.* (2019) [22] reported significantly higher leaf area and LAI in sorghum with 500 ppm nano ZnO foliar spray. Elizabeth *et al.* (2017) [5] also observed increased leaf area in carrot with ZnO NPs @ 100 ppm. Nano · SiO₂ at 600 ppm produced highest LAI through improved cell wall elasticity, water status, and nutrient uptake (Epstein, 1999; Ma & Yamaji, 2006) [6, 16]. Khademi *et al.* (2022) [11] reported increased chlorophyll content and fruit yield with Si NPs application in cucumber. T₃ (0 ppm ZnO+600 ppm SiO₂) consistently recorded highest LAI across all stages, indicating silicon alone is effective for leaf area development. The antagonistic effect in T₁₅ confirms severe suppression at high combined concentrations. Higher LAI increases photosynthetic capacity, light interception, and assimilate production for fruit development (Kumar *et al.*, 2016) [12].

3.1.5 Stem Diameter

The increase in stem diameter with Nano-ZnO up to 400 ppm demonstrates zinc's role in cambial activity and secondary growth through auxin synthesis (Cakmak *et al.*, 1989; Marschner, 2012) [3, 19]. Elizabeth *et al.* (2017) [5] reported increased plant height and root diameter in carrot with ZnO NPs. Nano · SiO₂ at 400 ppm produced highest stem diameter through silica deposition in cell walls, enhancing mechanical strength and lignin biosynthesis (Epstein, 1999; Ma & Yamaji, 2006; Liang *et al.*, 2007) [6, 16, 15]. T₂ (0 ppm ZnO+400 ppm SiO₂) consistently recorded maximum stem diameter across all stages, demonstrating silicon alone is effective for stem thickening. Khademi *et al.* (2022) [11] reported increased fruit yield and plant growth with Si NPs in cucumber. Increased stem diameter provides better mechanical support for fruits, improves vascular transport, and reduces lodging risk (Kumar *et al.*, 2016) [12].

Table 2: Effect of Foliar Application of Nano ZnO and SiO₂ on Vine length and No. of Leaves per plant of Parthenocarpic Cucumber at 30, 45, 60 days after sowing.

Sr. No.	Treatment	Treatment Combination	Vine length (cm)	No. of Leaves per plant				
30 DAS	45 DAS	60 DAS	30 DAS	45 DAS	60 DAS			
1	T ₀	NPs.ZnO(0ppm)+ NPs.SiO ₂ (0ppm) (control)	23.63	56.64	198.51	6.93	12.93	15.53
2	T ₁	NPs.ZnO(0ppm)+ NPs.SiO ₂ (200ppm)	34.11	82.23	210.29	9.07	15.13	17.93
3	T ₂	NPs.ZnO(0ppm)+ NPs.SiO ₂ (400ppm)	32.10	104.46	215.53	9.13	14.53	17.73
4	T ₃	NPs.ZnO(0ppm)+ NPs.SiO ₂ (600ppm)	44.70	122.34	219.52	9.87	15.53	19.67
5	T ₄	NPs.ZnO(300ppm)+ NPs.SiO ₂ (0ppm)	28.08	64.46	211.05	10.13	16.20	23.07
6	T ₅	NPs.ZnO(300ppm)+ NPs.SiO ₂ (200ppm)	42.54	119.02	217.92	9.20	16.40	24.53
7	T ₆	NPs.ZnO(300ppm)+ NPs.SiO ₂ (400ppm)	35.17	96.99	210.03	14.13	25.20	27.33
8	T ₇	NPs.ZnO(300ppm)+ NPs.SiO ₂ (600ppm)	37.51	100.44	214.24	10.33	20.00	22.20
9	T ₈	NPs.ZnO(400ppm)+ NPs.SiO ₂ (0ppm)	30.70	74.56	213.10	10.33	17.60	23.67
10	T ₉	NPs.ZnO(400ppm)+ NPs.SiO ₂ (200ppm)	36.06	92.00	212.47	13.33	22.20	25.40
11	T ₁₀	NPs.ZnO(400ppm)+ NPs.SiO ₂ (400ppm)	39.99	94.32	212.95	10.07	19.67	21.07
12	T ₁₁	NPs.ZnO(400ppm)+ NPs.SiO ₂ (600ppm)	40.88	117.91	216.32	11.07	18.20	22.40
13	T ₁₂	NPs.ZnO(500ppm)+ NPs.SiO ₂ (0ppm)	29.07	70.88	214.21	11.87	18.20	21.07
14	T ₁₃	NPs.ZnO(500ppm)+ NPs.SiO ₂ (200ppm)	36.81	87.34	213.80	10.07	18.20	22.60
15	T ₁₄	NPs.ZnO(500ppm)+ NPs.SiO ₂ (400ppm)	37.33	88.89	213.93	11.60	21.47	25.13
16	T ₁₅	NPs.ZnO(500ppm)+ NPs.SiO ₂ (600ppm)	25.36	59.56	207.88	8.13	14.93	17.13
		F Test	S	S	S	S	S	S
		SE(d)	6.09	20.68	4.77	0.43	0.58	1.04
		CD (p=0.05)	0.15	0.22	0.85	0.88	1.18	2.12

Table 3: Effect of Foliar Application of Nano ZnO and SiO₂ on No. of Branches per plant and Leaf Area Index of Parthenocarpic Cucumber at 30, 45, 60 days after sowing.

Sr. No.	Treatment	Treatment Combination	No. of Branches per plant	Leaf Area Index				
30 DAS	45 DAS	60 DAS	30 DAS	45 DAS	60 DAS			
1	T ₀	NPs.ZnO(0ppm)+ NPs.SiO ₂ (0ppm) (control)	1.80	3.60	7.60	44.07	92.33	160.47
2	T ₁	NPs.ZnO(0ppm)+ NPs.SiO ₂ (200ppm)	2.47	4.20	8.20	57.87	102.13	169.47
3	T ₂	NPs.ZnO(0ppm)+ NPs.SiO ₂ (400ppm)	2.67	4.20	8.60	58.47	98.93	171.27
4	T ₃	NPs.ZnO(0ppm)+ NPs.SiO ₂ (600ppm)	2.60	4.47	10.00	61.87	108.33	184.67

5	T ₄	NPs.ZnO(300ppm)+ NPs.SiO ₂ (0ppm)	2.53	5.07	9.40	64.53	167.93	194.27
6	T ₅	NPs.ZnO(300ppm)+ NPs.SiO ₂ (200ppm)	4.07	8.40	12.27	96.93	195.13	247.07
7	T ₆	NPs.ZnO(300ppm)+ NPs.SiO ₂ (400ppm)	3.07	7.60	11.00	91.73	184.33	181.47
8	T ₇	NPs.ZnO(300ppm)+ NPs.SiO ₂ (600ppm)	3.20	6.47	10.87	72.27	161.93	182.27
9	T ₈	NPs.ZnO(400ppm)+ NPs.SiO ₂ (0ppm)	3.53	6.73	12.73	82.33	163.73	193.67
10	T ₉	NPs.ZnO(400ppm)+ NPs.SiO ₂ (200ppm)	2.40	5.13	11.07	69.20	156.93	198.47
11	T ₁₀	NPs.ZnO(400ppm)+ NPs.SiO ₂ (400ppm)	3.07	7.20	11.40	83.73	167.53	184.67
12	T ₁₁	NPs.ZnO(400ppm)+ NPs.SiO ₂ (600ppm)	3.20	6.67	12.27	85.00	161.93	180.47
13	T ₁₂	NPs.ZnO(500ppm)+ NPs.SiO ₂ (0ppm)	4.87	9.00	13.20	98.60	198.53	249.07
14	T ₁₃	NPs.ZnO(500ppm)+ NPs.SiO ₂ (200ppm)	2.93	7.20	11.80	92.13	182.93	196.47
15	T ₁₄	NPs.ZnO(500ppm)+ NPs.SiO ₂ (400ppm)	3.80	8.00	12.47	96.07	193.33	242.67
16	T ₁₅	NPs.ZnO(500ppm)+ NPs.SiO ₂ (600ppm)	2.20	4.07	7.80	52.67	94.93	160.87
		F Test	S	S	S	S	NS	NS
		SE(d)	0.77	1.73	1.85	17.56	38.83	28.56
		CD (p=0.05)	0.41	0.30	0.70	3.52	0.07	0.83

Table 4: Effect of Foliar Application of Nano ZnO and SiO₂ on Stem Diameter of Parthenocarpic Cucumber at 30, 45, 60 days after sowing.

Sr.No.	Treatment	Treatment Combination	Stem Diameter (mm)		
30 DAS	45 DAS	60 DAS			
1	T ₀	NPs.ZnO(0ppm)+NPs.SiO ₂ (0ppm)(control)	2.33	5.20	6.47
2	T ₁	NPs.ZnO(0ppm)+NPs.SiO ₂ (200ppm)	2.73	5.60	7.40
3	T ₂	NPs.ZnO(0ppm)+NPs.SiO ₂ (400ppm)	3.20	6.33	7.53
4	T ₃	NPs.ZnO(0ppm)+NPs.SiO ₂ (600ppm)	3.27	7.20	7.40
5	T ₄	NPs.ZnO(300ppm)+NPs.SiO ₂ (0ppm)	4.07	7.20	7.53
6	T ₅	NPs.ZnO(300ppm)+NPs.SiO ₂ (200ppm)	7.40	9.20	13.27
7	T ₆	NPs.ZnO(300ppm)+NPs.SiO ₂ (400ppm)	6.60	7.93	12.07
8	T ₇	NPs.ZnO(300ppm)+NPs.SiO ₂ (600ppm)	4.80	7.53	9.73
9	T ₈	NPs.ZnO(400ppm)+NPs.SiO ₂ (0ppm)	7.67	9.40	13.60
10	T ₉	NPs.ZnO(400ppm)+NPs.SiO ₂ (200ppm)	4.67	7.20	7.67
11	T ₁₀	NPs.ZnO(400ppm)+NPs.SiO ₂ (400ppm)	6.53	7.80	10.80
12	T ₁₁	NPs.ZnO(400ppm)+NPs.SiO ₂ (600ppm)	7.20	8.33	12.87
13	T ₁₂	NPs.ZnO(500ppm)+NPs.SiO ₂ (0ppm)	5.13	7.67	9.20
14	T ₁₃	NPs.ZnO(500ppm)+NPs.SiO ₂ (200ppm)	6.40	7.87	11.27
15	T ₁₄	NPs.ZnO(500ppm)+NPs.SiO ₂ (400ppm)	6.33	7.93	11.87
16	T ₁₅	NPs.ZnO(500ppm)+NPs.SiO ₂ (600ppm)	2.73	5.40	6.80
		F Test	S	S	S
		SE(d)	1.84	1.22	2.52
		CD (p=0.05)	0.61	0.65	0.58

3.2.1 Total Soluble Solids (TSS - °Brix)

The maximum TSS (5.113 °Brix) was recorded in T₃ (0 ppm ZnO + 600 ppm SiO₂), followed by T₂ (0 ppm ZnO + 400 ppm SiO₂) with 4.880 °Brix and T₅ (300 ppm ZnO + 200 ppm SiO₂) with 4.400 °Brix. Among Nano-ZnO concentrations, 400 ppm recorded the highest TSS (4.333 °Brix), while 500 ppm recorded the lowest (3.852 °Brix). Among Nano · SiO₂ concentrations, 400 ppm recorded the highest (4.532°Brix), while 0 ppm recorded the lowest (3.733 Ω °Brix). The minimum TSS (3.180°Brix) was observed in T₁₅ (500 ppm ZnO + 600 ppm SiO₂), which was even lower than the control T₀ (3.340 °Brix). The maximum TSS in T₃ demonstrates that silicon alone is highly effective for improving fruit sweetness. *Silicon* enhances sugar accumulation by improving photosynthetic efficiency, increasing sugar production, and enhancing assimilate translocation to fruits (Epstein, 1999; Ma & Yamaji, 2006; Liang *et al.*, 2007) [6, 16, 15]. Khademi *et al.* (2022) [11] reported that Si NPs increased TSS by 11% in cucumber. The 53% improvement over control confirms silicon's significant role in carbohydrate metabolism. Zinc at 400 ppm increased TSS through its role as a cofactor for enzymes in photosynthesis and sugar synthesis (Cakmak *et al.*, 1989; Marschner, 2012) [3, 19]. Ahmad *et al.* (2021) [1] reported increased TSS with Zn foliar application in tomato. The decline at 500 ppm indicates zinc toxicity impairing carbohydrate metabolism (Hafeez *et al.*, 2013) [9]. The antagonistic effect in T₁₅, with TSS lower than control,

indicates that high combined concentrations severely impair sugar accumulation through competitive inhibition and possible zinc-silicate complexation (Ma *et al.*, 2007) [17]. Higher TSS improves fruit taste, consumer preference, and market value (Kumar *et al.*, 2016) [12].

3.2.2 pH of Fruit

The maximum pH (6.41) was recorded in T₃ (0 ppm ZnO + 600 ppm SiO₂), followed by T₅ (300 ppm ZnO + 200 ppm SiO₂) with 6.29 and T₁₄ (500 ppm ZnO + 400 ppm SiO₂) with 6.13. Among Nano-ZnO concentrations, 400 ppm recorded the highest pH (6.01), while 500 ppm recorded the lowest (5.62). Among Nano · SiO₂ concentrations, 400 ppm recorded the highest (6.01), while 0 ppm recorded the lowest (5.58). The minimum pH (5.21) was observed in T₁₅ (500 ppm ZnO+600 ppm SiO₂), which was lower than the control T₀ (5.28). The maximum pH in T₃ demonstrates silicon's role in maintaining optimal fruit pH through improved nutrient balance and reduced acidity (Epstein, 1999; Ma & Yamaji, 2006; Liang *et al.*, 2007) [6, 16, 15]. Cucumber fruits typically have pH values of 5.5-6.5, and the optimal pH achieved in T₃ (6.41) contributes to better taste and storage quality. Gustavo *et al.* (2020) reported that foliar Si application improved fruit quality parameters in cucumber. Zinc at 400 ppm increased pH through its influence on organic acid metabolism and sugar-acid balance (Cakmak *et al.*, 1989; Marschner, 2012) [3, 19]. The decline at 500 ppm indicates zinc toxicity disrupting fruit

metabolism (Hafeez *et al.*, 2013) ^[9]. The antagonistic effect in T₁₅ with pH lower than control confirms that high combined concentrations disrupt fruit metabolism through competitive inhibition (Ma *et al.*, 2007) ^[17]. Optimal pH improves fruit taste, flavor, consumer acceptance, and shelf life (Kumar *et al.*, 2016) ^[12].

3.2.3 Physiological Loss of Weight (PLW -%)

The lowest PLW (4.027%) was recorded in T₁₅ (500 ppm ZnO + 600 ppm SiO₂) and T₁₄ (500 ppm ZnO + 400 ppm SiO₂), indicating the best post-harvest shelf life. Among Nano-ZnO concentrations, 500 ppm recorded the lowest PLW (4.528%), while 400 ppm recorded the highest (4.973%). Among Nano · SiO₂ concentrations, 0 ppm recorded the lowest PLW (4.605%), while 400 ppm recorded the highest (5.052%). The highest PLW (5.427%) was observed in T₃ (0 ppm ZnO + 600 ppm SiO₂), which was even higher than the control T₀ (4.440%). The lowest PLW in T₁₅ indicates that high concentrations of both nanoparticles together improve post-harvest shelf life. This may be due to zinc strengthening cell walls, reducing respiration rate, and delaying senescence (Marschner, 2012; Hafeez *et al.*, 2013) ^[19, 9]. Zinc at 500 ppm improved shelf life through enhanced cell wall integrity and reduced transpirational water loss. The highest PLW in T₃ (0 ppm ZnO + 600 ppm SiO₂), higher than control, indicates that silicon alone without zinc resulted in poor shelf life, possibly due to increased fruit water content or altered fruit structure (Epstein, 1999; Ma & Yamaji, 2006) ^[6, 16]. Lower PLW extends shelf life, reduces post-harvest losses, and improves marketability (Kumar *et al.*, 2016) ^[12].

3.2.4 Fruit Firmness: The maximum firmness (5.86) was recorded in T₃ (0 ppm ZnO+600 ppm SiO₂) ·, followed by

T₁₁ (400 ppm ZnO+ 600 ppm SiO₂) with 5.24 and T₂ (0 ppm ZnO + 400 ppm SiO₂) with 5.21. Among Nano-ZnO concentrations, 400 ppm recorded the highest firmness (4.49), while 500 ppm recorded the lowest (3.50). Among Nano · SiO₂ concentrations, 400 ppm recorded the highest (4.60), while 0 ppm recorded the lowest (3.14). The minimum firmness (2.32) was observed in the control T₀, while T₁₅ recorded only 2.51. The maximum firmness in T₃ demonstrates that silicon alone is highly effective for improving fruit firmness through silica deposition in cell walls, enhancing mechanical strength, and reducing softening (Epstein, 1999; Ma & Yamaji, 2006; Liang *et al.*, 2007) ^[6, 16, 15]. Silicon also enhances calcium uptake, essential for cell wall stability. The 153% improvement over control confirms silicon's critical role in fruit texture. Khademi *et al.* (2022) ^[11] reported that Si NPs at 100-300 mg L⁻¹ produced different fruit firmness in cucumber cultivars. Gustavo *et al.* (2020) also reported that foliar Si application significantly increased fruit firmness in cucumber. Zinc at 400 ppm increased firmness through its role in cell wall synthesis and lignin formation (Cakmak *et al.*, 1989; Marschner, 2012) ^[3, 19]. Ahmad *et al.* (2021) ^[1] reported improved firmness with Zn foliar application in tomato. The decline in firmness at 500 ppm zinc indicates zinc toxicity, which weakens cell wall structure and reduces fruit quality (Hafeez *et al.*, 2013) ^[9]. The antagonistic effect in T₁₅ with firmness barely above control indicates that high zinc weakens cell wall structure through competitive inhibition (Ma *et al.*, 2007) ^[17]. Higher firmness improves fruit texture, resistance to mechanical damage during harvesting and transport, extends post-harvest shelf life, enhances consumer preference, and leads to better market prices (Kumar *et al.*, 2016) ^[12].

Table 5: Effect of Foliar Application of Nano ZnO and SiO₂ on Quality parameters of Parthenocarpic Cucumber at the time of Harvest and Physiological loss of Weight in (%) after 3 days of harvest.

Sr.No.	Treatment	Treatment Combination	Quality Parameters			
TSS(0Brix)	pH	Firmness	Physiological loss of Weight in (%)			
1	T ₀	NPs.ZnO(0ppm)+NPs.SiO2(0ppm)(control)	3.34	5.28	2.32	6.93
2	T ₁	NPs.ZnO(0ppm)+NPs.SiO2(200ppm)	3.70	5.56	3.21	9.07
3	T ₂	NPs.ZnO(0ppm)+NPs.SiO2(400ppm)	4.01	5.79	3.69	9.13
4	T ₃	NPs.ZnO(0ppm)+NPs.SiO2(600ppm)	3.89	5.70	3.33	9.87
5	T ₄	NPs.ZnO(300ppm)+NPs.SiO2(0ppm)	3.64	5.46	3.23	10.13
6	T ₅	NPs.ZnO(300ppm)+NPs.SiO2(200ppm)	4.40	5.95	5.03	9.20
7	T ₆	NPs.ZnO(300ppm)+NPs.SiO2(400ppm)	4.59	5.43	4.85	14.13
8	T ₇	NPs.ZnO(300ppm)+NPs.SiO2(600ppm)	3.51	6.02	3.05	10.33
9	T ₈	NPs.ZnO(400ppm)+NPs.SiO2(0ppm)	4.88	6.29	5.21	10.33
10	T ₉	NPs.ZnO(400ppm)+NPs.SiO2(200ppm)	4.21	5.93	3.92	13.33
11	T ₁₀	NPs.ZnO(400ppm)+NPs.SiO2(400ppm)	4.21	6.13	4.16	10.07
12	T ₁₁	NPs.ZnO(400ppm)+NPs.SiO2(600ppm)	4.83	6.41	5.11	11.07
13	T ₁₂	NPs.ZnO(500ppm)+NPs.SiO2(0ppm)	5.11	6.11	5.86	11.87
14	T ₁₃	NPs.ZnO(500ppm)+NPs.SiO2(200ppm)	3.76	5.49	2.75	10.07
15	T ₁₄	NPs.ZnO(500ppm)+NPs.SiO2(400ppm)	4.53	6.20	5.24	11.60
16	T ₁₅	NPs.ZnO(500ppm)+ NPs.SiO2(600ppm)	3.18	5.21	2.51	8.13
		F Test	S	S	S	S
		SE(d)	0.58	0.37	1.12	0.46
		CD (p=0.05)	0.17	0.09	0.44	0.01

Conclusion

The present investigation, it is recorded that the maximum yield at parthenocarpic cucumber was recorded at T₁₁ (400 ppm ZnO+600 ppm SiO₂) proved best for leaf production (34.87 leaves at 60 DAS). T₃ (0 ppm ZnO + 600 ppm SiO₂) proved best for branching (13.20), leaf area index (249.07),

earliest flowering (23.53 days), and earliest harvest (40.67 days). T₂ (0 ppm ZnO+400 ppm SiO₂) proved best for stem diameter (13.60 mm). T₃ proved best for vine length at 30 and 60 DAS (44.70 cm and 219.52 cm), while T₁₂ (500 ppm ZnO+0 ppm SiO₂) proved best at 45 DAS (122.34 cm). T₃ (0 ppm ZnO+600 ppm SiO₂) proved best for TSS (5.113

°Brix), pH (6.41), and fruit firmness (5.86). T₁₅ (500 ppm ZnO + 600 ppm SiO₂) proved best for post-harvest shelf life (lowest PLW of 4.027%). For maximizing growth and quality, T₃ (0 ppm ZnO+600 ppm SiO₂) is the most effective treatment. The treatment T₁₅ (500 ppm ZnO + 600 ppm SiO₂) showed severe antagonistic effects and should be strictly avoided.

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