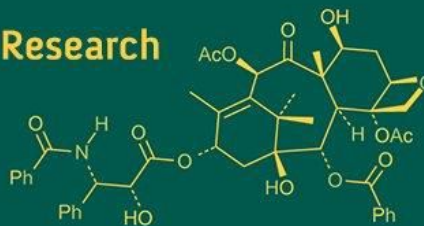


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(8): 1236-1241
www.biochemjournal.com
Received: 14-06-2025
Accepted: 18-07-2025

Manavi

M.Sc. Scholar, Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, Uttar Pradesh, India

Samir E Topno

Assistant Professor, Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, Uttar Pradesh, India

Annjoe V Joseph

Assistant Professor, Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, Uttar Pradesh, India

Corresponding Author:**Manavi**

M.Sc. Scholar, Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, Uttar Pradesh, India

Effect of Ga₃, Nano zinc and Nano boron on seed germination, plant growth and establishment of Papaya cv. Red lady

Manavi, Samir E Topno and Annjoe V Joseph

DOI: <https://www.doi.org/10.33545/26174693.2025.v9.i8Sr.5341>

Abstract

The experiment was carried out at Department of Horticulture, Naini Agricultural Institute, SHUATS, Prayagraj during the year 2024- 2025. The experiment was laid out in Randomized Block Design comprising of 9 treatments viz., T₀ Control, T₁ Nano Zinc @ 10 ppm (Foliar application), T₂ Nano Zinc @ 20 ppm (Foliar application), T₃ Nano Zinc @ 30 ppm (Foliar application), T₄ Nano Zinc @ 40 ppm (Foliar application), T₅ Nano Boron @ 15ppm (Foliar application), T₆ Nano Boron @ 20ppm (Foliar application), T₇ Nano Boron @ 25ppm (Foliar application), T₈ Nano Boron @ 25ppm (Foliar application) with three replications. The treatments in each replication were allotted randomly. The Papaya seeds were pre-treated with GA₃ @ 200ppm GA₃ before being sown in pot trays with the potting mixture consisting of soil, cocopeat and FYM in 1:1:1 ratio. The observations were recorded are days to germination (7.4 days), germination percentage (91.8%), seedling height (20.88 cm), number of leaves (18.07), stem diameter (13.22 mm), chlorophyll content (38.54), leaf area (83.71 cm²), leaf area index (17.46), shoot : root ratio (4.19), specific leaf area (1.15 cm²mg⁻¹), absolute growth rate (0.21 cmday⁻¹) and survival percentage (84.83%). The results revealed that the treatment T₇ was found to be the most suitable in all the above mentioned parameters.

Keywords: Papaya, ga₃, nano zinc and nano boron

Introduction

Papaya (*Carica papaya* L.), often called the “wonder fruit of the tropics,” is native to tropical America (Hafner, 1990) [11]. It was introduced to India via Malacca from the Philippines in the early sixteenth century (Singh, 1990). It belongs to the family Caricaceae, consisting of six genera and about 35 species, and its closest relative is *Vasconellea* with 21 species. Initially grown in home gardens, papaya’s adaptability to diverse soils and climates with year-round fruiting helped transform it into a major commercial crop (Drew et al., 1998). India currently leads global papaya production, though annual yields fluctuate due to its short lifespan. Key producing states include Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, West Bengal, Chhattisgarh, Tamil Nadu, Assam, Kerala and Uttar Pradesh (Sharma et al., 2023). In 2023, papaya cultivation in India covered approximately 146,000 ha with an output of 5.54 million t (NHB, 2023), and around 5.95 million t were estimated in the fiscal year 2020–21 (Anonymous, 3rd estimate). Its low input requirements, rapid growth and high profitability have made it a widely cultivated fruit crop.

Papaya is valued for its nutritional and therapeutic properties. It contains the digestive enzyme papain, antioxidants such as lycopene, and carotenoid pigments like caricaxanthin. These compounds exhibit anticancer potential, with papaya juice showing *et al* activity against liver cancer cells (Meena et al., 2017) [14]. Regular consumption may reduce the risk of cardiovascular diseases, diabetes and cancer. A small papaya (150 g) contains 59 kcal, 157% of the RDI for vitamin C, 33% for vitamin A, 14% folate, 11% potassium, trace minerals including calcium and magnesium, vitamins B₁, B₃, B₅, E and K, 3 g fiber, 1 g protein and 15 g carbohydrates (Hardisson et al., 2001) [12]. Papain is used in food processing and pharmaceuticals for protein digestion, meat tenderization and therapeutic applications (Dayeswari et al., 2017; Quenum, 2001) [7, 19].

Papaya is a semi-woody, usually unbranched evergreen tree reaching 5–10 m in height, with large palmately lobed leaves (120–125 cm petioles) clustered at the apex. It is a polygamous

species with male, female and hermaphrodite flowers. Hermaphrodite flowers, which bear both stamens and pistils, produce the edible fruits. Fruits range from cylindrical to pyriform (12–45 cm long, 10–30 cm diameter) and change colour from green to yellow-orange when ripe. Seeds are black and located in a central cavity, while the orange flesh owes its colour to carotenoids like caricaxanthin.

Propagation is mainly by seed, though germination is often slow and irregular due to the gelatinous sar. Removing this layer, rinsing seeds, and pre-soaking them in plant growth regulators improve germination and seedling vigour. Gibberellic acid (GA₃) is particularly effective at breaking dormancy and enhancing germination by mobilizing seed reserves (Bharadwaj, 2014; Mishra et al., 2017; Zanotti & Barros, 2014) [3, 15, 24].

Micronutrients like zinc and boron play a vital role in papaya growth and reproductive success. Zinc (Zn²⁺) is essential for enzyme activation, auxin synthesis, gene regulation, pollen production and oxidative stress protection (Brown et al., 1993; Hafees et al., 2013) [5, 10]. Boron is involved in sugar translocation, pollen-tube growth, fruit set and quality enhancement (Brady & Weil, 1996; Abd-Allah, 2006) [4, 1]. Foliar boron application reduces fruit cracking and improves yield in many fruit crops. Nanofertilizer application can increase nutrient efficiency and reduce environmental impact.

Methods and Materials

The experiment was conducted in 2024 at Shade Net-2, Department of Horticulture, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj. The site is located at 25.85° N latitude and 81.15° E longitude, at an altitude of 78 m above mean sea level. Prayagraj falls in a subtropical climate, where summer temperatures can exceed 48 °C and winters may drop to around 20 °C, occasionally with light frost. Hot, dry winds are frequent in summer, and the region receives an annual average rainfall of approximately 1013 mm, mainly during July to September. Weather data for the 2024–25 experimental period were obtained from the SHUATS agrometeorological observatory.

Seeds of papaya (*Carica papaya*) cv. Red Lady were procured from Krishni Paramarsh Kendra, Alopi Bagh, Prayagraj. Polybags (4 × 5 cm; 150 gauge) were sourced locally. Pot trays were prepared using a 1:1:1 mixture of soil, farmyard manure (FYM) and cocopeat, treated with copper oxychloride @ 2% as a fungicide. Single seeds were sown per cell, and light irrigation was provided twice daily, avoiding waterlogging. Before sowing, seeds were soaked in GA₃ @ 200 ppm for 24 hours to enhance germination.

Results and Discussion

Days taken for germination in Papaya - The minimum days taken for completion of germination (7.40) was recorded in T7 Nano Boron at 25 mg/L. While maximum days taken for completion of germination (9.70) were recorded in T0 (control).

Nano zinc and nano boron treatments significantly improved germination over the control (69.39%), with the highest rate (91.78%) in Nano Boron at 25 mg/L (T7), followed by T6 (20 mg/L) and T3 (Nano Zinc 30 mg/L). Optimal concentrations outperformed higher doses, and statistical validation (CD = 2.10, CV = 1.52%) confirmed the reliability of results. These findings, in line with (An et al.

2022) and (Biradar et al. 2023), highlight nanoparticles as effective tools for enhancing seed viability and crop productivity in regions like Prayagraj.

Germination percentage in Papaya - The maximum germination percentage (91.70%) was recorded in T7 Nano Boron at 25 mg/L. While minimum germination percentage (63.39%) was recorded in T0 (control).

Nano zinc and nano boron treatments markedly increased germination over the control (69.39%), with the highest value (91.78%) in Nano Boron at 25 mg/L (T7), followed by T6 (20 mg/L) and T3 (Nano Zinc 30 mg/L). Higher doses showed no further benefit, and statistical analysis (CD = 2.10, CV = 1.52%) confirmed the reliability of results. In line with (An et al. 2022) and (Biradar et al. 2023) these findings highlight nanoparticles as effective in enhancing seed viability and crop productivity in Prayagraj.

Seedling height (cm) in Papaya - The maximum seedling height recorded at 30 days (7.91 cm), 60 days (14.32 cm) and 90 days (20.88 cm) in T7 (Nano Boron at 25 mg/L). While minimum seedling height was recorded at 30 days (6.13cm), 60days (9.97cm) and 90 days (14.80 cm) in T0 (control).

Nano zinc and nano boron markedly increased seedling height at all stages (30, 60, and 90 DAS) over the control (14.80 cm at 90 DAS), with Nano Boron at 25 mg/L (T7) achieving the tallest growth (20.88 cm). The improvements, supported by statistical significance and a low CV (1.4%), are attributed to enhanced nutrient uptake and metabolic activity (An et al., 2022). These results, consistent with (Biradar et al. 2023) demonstrate the potential of nano-treatments for vigorous seedling establishment and better crop performance in regions like Prayagraj.

No. of leaves in Papaya - The maximum number of leaves was recorded at 30 days (6.00), 60days (12.00) and 90 days (18.07) in T7 (Nano Boron at 25 mg/L). While minimum number of leaves recorded at 30 days (4.40), 60 days (8.80) and 90 days (12.87) in T0 (control).

Nano zinc and nano boron significantly increased leaf number at all stages (30, 60, and 90 DAS) compared to the control (12.87 leaves at 90 DAS), with Nano Boron at 25 mg/L (T7) producing the highest count (18.07 leaves). These gains, confirmed by statistical significance (CD = 1.12) and a low CV (4.11%), are linked to enhanced photosynthesis and plant health (An et al., 2022). Consistent with (Biradar et al. 2023) the results show nano-nutrients as an effective means of promoting vigorous vegetative growth and improving yield potential in regions like Prayagraj.

Stem diameter (mm) in Papaya - The maximum stem diameter was recorded at 30 days (1.31 mm), 60 days (7.28 mm) and 90 days (13.22 mm) in T7 (Nano Boron at 25 mg/L). While minimum stem diameter was recorded at 30 days (0.81 mm), 60 days (5.27 mm) and 90 days (9.54 mm) in T0 (control).

Nano zinc and nano boron significantly increased stem diameter at all growth stages compared to the control (9.54 mm at 90 DAS), with Nano Boron at 25 mg/L (T7) producing the maximum girth (13.22 mm). These improvements, confirmed by statistical significance (CD = 0.60) and a low CV (2.90%), enhance plant structure and nutrient transport (An et al., 2022). Consistent with (Biradar et al. 2023) the results highlight nano-nutrients as an effective approach for stronger, more productive crops in regions like Prayagraj.

Chlorophyll content (SPAD Value) in Papaya: The maximum chlorophyll content was recorded at 30 days (31.95), 60 days (28.63) and 90 days (32.18) in T7 (Nano Boron at 25 mg/L). While the minimum chlorophyll content was recorded at 30 days (25.17), 60 days (28.63) and 90 days (32.18) in T0 (control).

Nano zinc and nano boron significantly increased chlorophyll content (SPAD value) at all stages compared to the control (32.18 at 90 DAS), with Nano Boron at 25 mg/L (T7) recording the highest value (38.54). These gains, statistically significant (CD = 1.69) with a low CV (2.80%), enhance photosynthetic efficiency and plant health (An *et al.*, 2022). In agreement with (Biradar *et al.* 2023), the results indicate nano-nutrients as a promising approach to improve crop productivity in regions like Prayagraj.

Leaf Area (cm²) in Papaya: The maximum leaf area was recorded at 60 days (54.34 cm²) and 90 days (71.29 cm²) in T7 (Nano Boron at 25 mg/L). While the minimum leaf area was recorded at 60 days (32.19 cm²) and 90 days (57.83 cm²).

Nano zinc and nano boron significantly increased chlorophyll content (SPAD value) at all stages compared to the control (32.18 at 90 DAS), with Nano Boron at 25 mg/L (T7) recording the highest value (38.54). These gains, statistically significant (CD = 1.69) with a low CV (2.80%), enhance photosynthetic efficiency and plant health (An *et al.*, 2022). In agreement with (Biradar *et al.* 2023), the results indicate nano-nutrients as a promising approach to improve crop productivity in regions like Prayagraj.

Leaf Area Index in Papaya - The maximum leaf area index was recorded at 60days (13.78) and 90 days (17.46) in T7 (Nano Boron at 25 mg/L). While the minimum leaf area index at 60 days (9.51) and 90 days (15.09) in T0 (control).

Nano zinc and nano boron significantly increased Leaf Area Index (LAI) at 60 and 90 DAS compared to the control (15.09 at 90 DAS), with Nano Boron at 25 mg/L (T7) recording the highest value (17.46). These statistically significant improvements (CD = 1.21) with a low CV (3.50%) enhance light interception and photosynthesis (An *et al.*, 2022). In line with (Biradar *et al.* 2023), the results confirm nano-nutrients as an effective approach for optimizing canopy development and boosting crop productivity in regions like Prayagraj.

Specific Leaf Area in Papaya: The maximum specific leaf area was recorded at 60 days (1.04 cm² mg⁻¹) and 90 days (1.15 cm² mg⁻¹) in T7 (Nano Boron at 25 mg/L). While minimum specific leaf area was recorded at 60 days (0.83 cm² mg⁻¹) and 90 days (0.93 cm² mg⁻¹) in T0 (control). Nano zinc and nano boron significantly increased Specific Leaf Area (SLA) at 60 and 90 DAS, with treated plants developing thinner, more expansive leaves for improved

light absorption. Nano Boron at 25 mg/L (T7) recorded the highest SLA (1.15 cm² mg⁻¹ at 90 DAS). These statistically significant gains, supported by a low CV (1.80%), enhance photosynthetic efficiency and plant productivity (An *et al.*, 2022). Consistent with (Biradar *et al.* 2023), the findings show nano-nutrients as an effective means to optimize plant structure and boost crop performance in regions like Prayagraj.

Shoot: Root ratio in Papaya: The maximum shoot: root ratio was recorded at 60days (3.78) and 90 days (4.19) in T7 (Nano Boron at 25 mg/L). While minimum shoot: root ratio was recorded at 60 days (2.75) and 90 days (3.80) in T0 (control).

Nano zinc and nano boron significantly increased the shoot: root ratio at 60 and 90 DAS compared to the control (3.80 at 90 DAS), with Nano Boron at 25 mg/L (T7) recording the highest value (4.19), followed by Nano Zinc at 40 mg/L (T4) with 4.04. These statistically significant gains (CD = 0.08) and the very low CV (1.2%) indicate enhanced biomass allocation to shoots, boosting photosynthesis and productivity (An *et al.*, 2022). In agreement with (Biradar *et al.* 2023), the results confirm nano-nutrients as a reliable strategy for balanced growth and higher yields in regions like Prayagraj.

Absolute Growth rate in Papaya - The maximum absolute growth rate was recorded at 90 days (0.21 cm day⁻¹) in T7 (Nano Boron at 25 mg/L). While minimum absolute rate was recorded at 90 days (0.15 cm day⁻¹) in T0 (control).

Nano zinc and nano boron significantly increased the Absolute Growth Rate (AGR) by 90 DAS compared to the control, with Nano Boron at 25 mg/L (T7) recording the highest value (0.21 cm day⁻¹). This improvement, confirmed by statistical significance (CD = 0.02) and a low CV (6.3%), supports faster biomass accumulation and potential for earlier harvests (An *et al.*, 2022). In line with (Biradar *et al.* 2023), the results highlight nano-nutrients as an effective strategy to enhance growth dynamics and agricultural productivity in regions like Prayagraj.

Survival percentage in Papaya - The maximum survival percentage was 84.83% recorded in T7 (Nano Boron at 25 mg/L). While minimum survival percentage was 59.17% recorded in T0 (control).

Nano zinc and nano boron significantly improved plant survival over the control (59.17%), with Nano Boron at 25 mg/L (T7) recording the highest rate (84.83%), followed by T6 (20 mg/L) and T2 (Nano Zinc 20 mg/L). These statistically significant gains (CD = 1.41) with a very low CV (1.1%) enhance crop establishment and yield potential (An *et al.*, 2022). Consistent with (Biradar *et al.* 2023), the findings confirm nano-nutrients as an effective approach to boost plant resilience in regions like Prayagraj.

Table 1: Effect of Ga₃, nano zinc and nano boron on seed germination, plant growth and establishment of Papaya cv. Red lady

Sl. No.	Treatment No.	Treatment details	Parameters										
			Days taken for germination	Germination %	No. of leaves	Stem diameter	Chlorophyll content	Leaf Area	Leaf Area Index	Specific Leaf Area	Shoot: Root Ratio	Absolute Growth Rate	Survival %
1.	T ₀	Control (Water Spray)	9.27	69.39	12.87	9.54	32.18	57.83	15.09	0.93	3.80	0.15	59.17
2.	T ₁	Nano Zinc @ 10 mg/L	7.67	77.21	16.53	10.91	33.67	76.63	16.67	1.06	4.04	0.18	64.90
3.	T ₂	Nano Zinc @ 20 mg/L	8.13	74.46	15.40	11.55	33.51	74.39	16.67	1.06	4.09	0.18	79.69

4.	T ₃	Nano Zinc @ 30 mg/L	7.93	80.66	16.73	11.72	33.64	75.61	16.47	1.07	4.02	0.18	73.33
5.	T ₄	Nano Zinc @ 40 mg/L	7.87	75.38	15.13	12.09	36.04	74.50	16.69	1.08	4.04	0.17	79.27
6.	T ₅	Nano Boron @ 15 mg/L	8.07	79.78	15.80	11.94	36.07	76.63	16.53	1.06	4.06	0.16	62.35
7.	T ₆	Nano Boron @ 20 mg/L	7.67	85.60	17.07	12.86	36.60	77.63	16.71	1.09	4.13	0.19	80.55
8.	T ₇	Nano Boron @ 25 mg/L	7.40	91.78	18.07	13.22	38.54	83.71	17.46	1.15	4.19	0.21	84.83
9.	T ₈	Nano Boron @ 30 mg/L	7.93	81.32	14.80	11.96	35.01	71.29	15.50	1.08	4.07	0.18	74.48
		Test of Significance	S	S	S	S	S	S	S	S	S	S	S
		S.Ed±	0.12	0.15	0.38	0.20	0.56	0.36	0.40	0.01	0.03	0.01	0.47
		CD at 5%	0.36	0.45	1.12	0.60	1.69	1.06	1.21	0.03	0.08	0.02	1.41
		CV	2.62	1.40	4.11	2.90	2.80	0.80	3.50	1.80	1.20	6.30	1.10

Table 2: Cost of treatments for establishment of Papaya cv. Red lady

Notation	Treatment details	Ga3 @ 10g (Rs. 1500)		Nano Zinc @ 50g (Rs. 1500)		Nano Boron @ 25g (Rs. 8000)		Cost Treatment (Rs.)
		For 1000 plants Qty	Amount (Rs.)	For 1000 plants Qty	Amount (Rs.)	For 1000 plants Qty	Amount (Rs.)	
T0	Control (Water Spray)	-	-	-	-	-	-	-
T1	Nano Zinc @ 10mg/L	0.6	90	0.11g	3.3	-	-	93.3
T2	Nano Zinc @ 20mg/L	0.6	90	0.22g	6.6	-	-	96.6
T3	Nano Zinc @ 30mg/L	0.6	90	0.33g	9.9	-	-	99.9
T4	Nano Zinc @ 40mg/L	0.6	90	0.44g	13.2	-	-	103.2
T5	Nano Boron @ 15mg/L	0.6	90	-	-	0.16g	51.2	141.2
T6	Nano Boron @ 20mg/L	0.6	90	-	-	0.22g	70.4	160.4
T7	Nano Boron @ 25mg/L	0.6	90	-	-	0.27g	86.4	176.4
T8	Nano Boron @ 30mg/L	0.6	90	-	-	0.33g	105.6	195.6

Table 3: Cost of cultivation of Papaya cv. Red lady

Notations	Polybag (6*4 inch)			Seed price (1000 seeds Rs. 7400)		Labour for pot filling			Potting mixture (FYM: Soil: Cocopeat) 1:1:1 ratio						Miscellaneous charges	Cost of cultivation for 1000 plants
	Qty.	Rate (Rs.)	Amt. (Rs.)	Qty (No. of seeds)	Amt. (Rs.)	Labour	Rate (Rs.)	Amt. (Rs.)	FYM Qty. (kg)	Rate (Rs.)	Amt. (Rs.)	Cocopeat Qty. (kg)	Rate (Rs.)	Amt. (Rs.)		
T0	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,820.00
T1	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,913.30
T2	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,916.60
T3	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,919.90
T4	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,923.20
T5	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,961.20
T6	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,980.40
T7	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	12,996.40
T8	1000	2.66	2660	1000	7400	2	350	700	125	2	250	125	14	1750	60	13,015.60

Table 4: Economics for establishment of Papaya cv. Red lady

Notations	Cost of Cultivation (Rs.)	Selling Price (Rs.)	Total Seedling	Selling Price (Rs.)	Gross Return (Rs.)	Net Return (Rs.)	BC Ratio
	(Rs.)	(Rs.)		(Rs.)	(Rs.)	(Rs.)	(Rs.)
T0	20100	44	591.67	44	26033.3	13,213.33	1.03
T1	20433.3	44	649.03	44	28557.5	15,644.17	1.21
T2	20436.6	44	796.87	44	35062.1	22,145.53	1.71
T3	20439.9	44	733.27	44	32263.7	19,343.83	1.50
T4	20443.2	44	792.67	44	34877.3	21,954.13	1.70
T5	20481.2	44	623.50	44	27434.0	14,472.80	1.12
T6	20500.4	45	805.50	45	36247.5	23,267.10	1.79
T7	20516.4	45	848.33	45	38175.0	25,178.60	1.94
T8	20535.6	44	744.77	44	32769.7	19,754.13	1.52

Table 5: Cost of establishment of Papaya cv. Red lady

Sl no.	Particulars	Unit	Qty.	Rate/Unit (Rs.)	Cost (Rs. / ha)
A	Land preparation				
1.	Ploughing	Hours	4	800	3,200
2.	Harrowing	Hours	4	800	3,200
3.	Layout for pit/ Ring basin	Rs 100/25 pits	3086	4	12,344
4.	Cost of pit preparation	Labour	2	350	700
B	Transplanting				
1.	Cost of plant	No.	3086	30	92,580
2.	Transplanting of plant	Labour	20	350	7,000
C	Foliar application				
1.	Labour for application of fertilizer	Labour	6	350	2,100
D	Irrigation				
	2 labours per irrigation (6 days interval for 2 hrs)	Water	12	350	4,200
E	Interculture operations				
	Weeding (6 labours per weeding)	Labour	12	350	4,200
I	Rental value of land	Months	3	1000	3,000
J	Supervision charges	Months	3	500	1,500
K	Transportation				5,000
L	Assuming establishment survival percentage rate to be 70% (Extra plants)		414	30	12,420
		Total fixed cost (Rs. / ha)			1,51,444

Conclusion

This study demonstrates the effectiveness of GA₃ seed pre-treatment (200 ppm) combined with nano boron foliar application (25 mg/L) in improving papaya germination, growth, and seedling establishment. The best treatment (T₇) reduced germination time to 7.40 days and achieved 91.78% germination, producing vigorous seedlings with 20.88 cm plant height, 18.07 leaves, 13.22 mm stem diameter, and 38.54 SPAD chlorophyll content at 90 days after sowing. Leaf area (83.71 cm²), leaf area index (17.46), and specific leaf area (1.15 cm²/mg) were also superior, indicating enhanced photosynthetic efficiency and resource utilization. Nursery survival reached 84.83%, supporting better establishment for field planting.

Economic evaluation revealed that T₇ generated net returns of ₹25,178.60 per 1000 plants with a benefit-cost ratio of 1.94, highlighting its commercial viability. The superior performance of nano boron is attributed to its higher bioavailability, efficient nutrient delivery, and its role in cell wall synthesis, sugar transport, and metabolic activities. This integrated approach provides a sustainable and profitable solution to the challenges of poor germination and weak seedling vigour in papaya. It establishes a practical protocol for nurseries and supports the adoption of nanotechnology in tropical fruit crop production systems.

References

1. Abd Allah ASE. Effect of spraying some macro and micro nutrients on fruit set, yield and fruit quality of Washington Navel orange trees. *J Appl Sci Res.* 2006;2(11):1059-63.
2. Anonymous. Third advance estimates of horticultural crops 2020–21. Ministry of Agriculture and Farmers Welfare, Government of India; 2021.
3. Bharadwaj A. Effect of gibberellic acid on seed germination and seedling growth of papaya (*Carica papaya* L.). *J Appl Nat Sci.* 2014;6(2):450-3.
4. Brady NC, Weil RR. The nature and properties of soils. 11th ed. Prentice Hall; 1996.
5. Brown PH, Cakmak I, Zhang Q. Form and function of zinc in plants. *Plant Soil.* 1993;155(1):241-6.
6. Chako EK, Singh RM. Studies on the germination of papaya (*Carica papaya*) seeds. *Indian J Hortic.* 1966;23(3):138-43.
7. Dayeswari G, Lalitha A, Kumari R. Papaya (*Carica papaya*): A source of nutraceuticals and health benefits. *Int J Chem Stud.* 2017;5(4):1366-70.
8. Drew RA, Magdalita PM, O'Brien CM. Development of papaya hybrids with tolerance to Papaya Ringspot Virus. *Aust J Exp Agric.* 1998;38(5):489-94.
9. El Salhy FT, Ali SA, Farag FM. Nano fertilizer applications in fruit crops: Efficiency and environmental safety. *J Plant Nutr.* 2021;44(11):1678-90.
10. Hafees M, Kumar N, Sharma R. Role of micronutrients in plant growth and their management. *J Agric Sci.* 2013;5(2):97-107.
11. Hafmer C. Tropical and subtropical fruit crops. Springer; 1990.
12. Hardisson A, Rubio C, Baez A. Mineral composition of papaya (*Carica papaya*) and its importance in the human diet. *Food Chem.* 2001;74(3):347-51.
13. IMD. Agro climatic data of Prayagraj. Indian Meteorological Department; 2023.
14. Meena R, Singh S, Singh R. Anticancer potential of papaya (*Carica papaya*) and its constituents: A review. *J Pharmacogn Phytochem.* 2017;6(5):988-93.
15. Mishra R, Patel R, Singh D. Effect of GA₃ on seed germination and early seedling growth in tropical fruit crops. *Int J Curr Microbiol Appl Sci.* 2017;6(9):1123-9.
16. Morwal BR, Das B. Role of boron in fruit set and quality improvement of pomegranate. *Hortic Plant J.* 2021;7(4):211-8.
17. Naderi MR, Danesh Shahraki A, Rashid S. Application of nanotechnology in agriculture and its role in sustainable crop production. *J Plant Nutr.* 2011;34(12):2000-20.
18. NHB. Area and production of horticultural crops. National Horticulture Board, India; 2023.
19. Quenum B. Papain (*Carica papaya*): Properties and applications in food and pharmaceuticals. *J Food Biochem.* 2001;25(2):107-20.

20. Selivanov S, Zorin V. Efficiency of nano fertilizer application in horticultural crops. Russ Agric Sci. 2001;27(4):45-9.
21. Sharma RR, Singh D, Saxena S. Status of papaya (*Carica papaya*) production in India: Trends and prospects. Indian Hortic J. 2023;13(1):11-8.
22. Singh RS. Introduction and spread of papaya (*Carica papaya*) in India. ICAR Publication; 1990.
23. Singh SK, Singh R, Tiwari DK. Effect of boron on fruit cracking and yield in pomegranate. Indian J Hortic. 2003;60(2):128-32.
24. Zanotti CM, Barros M. Role of gibberellins in seed germination and seedling establishment of tropical fruit crops. Sci Hortic. 2014;175:106-13.