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Influence of different Growing Media and Plant Growth Regulators on Seedling Growth in Papaya (*Carica papaya* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

The study was conducted in the Horticulture Experiment Field, Department of Horticulture, School of Advanced Agricultural Sciences and Technology, Chhatrapati Shahu Ji Maharaj University, Kanpur, during the year 2026. The primary objective was to evaluate the influence of diverse growing media and plant growth regulators (PGRs), particularly Gibberellic Acid (GA_3) and Naphthalene Acetic Acid (NAA), on the germination behaviour and seedling development of papaya under nursery conditions. The experiment included nine treatments with different combinations of PGRs and media: soil alone (control), soil mixed with vermicompost, Perlite and cocopeat in various proportions, and treated with GA_3 or NAA at 50 ppm. The treatments were assessed for their impact on seed germination, imbibition period, speed of emergence, seedling vigour, survival percentage, and morphological growth attributes such as seedling height, number of leaves, leaf area, root number and length, stem girth, fresh biomass and shoot-to-root ratio. Several

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germination parameters were recorded, including imbibition period, speed of emergence, germination percentage, seedling vigour index, and survival percentage. Seedling growth parameters such as seedling height, number of leaves, leaf area, stem girth, number and length of roots, fresh weight of shoot and root, and shoot-to-root ratio were evaluated at 30 and 45 days after sowing (DAS). The results revealed significant differences among the treatments. Treatment T4 (NAA @ 50 ppm with soil + vermicompost + Perlite in equal proportions) exhibited the shortest imbibition period (9.00 days), the highest speed of emergence (92.63), and the highest germination percentage (73.33%). It also produced the most vigorous seedlings with a seedling vigour index of 795.67 and the highest survival percentage of 95.83%. NAA treatments, particularly T4, consistently outperformed other treatments in terms of early emergence and uniform germination, due to enhanced enzymatic activity and rapid mobilization of seed reserves. On the other hand, Treatment T8 (GA3 @ 50 ppm with the same media composition of soil, vermicompost and Perlite) was particularly effective in promoting vegetative growth and root development. It recorded the maximum seedling height (15.01 cm), number of leaves (9.40), leaf area (34.37 cm^2), root length (12.50 cm), number of roots (21.87), fresh shoot weight (4.20 g), fresh root weight (0.92 g), and shoot:root ratio (4.55). This indicates that GA_3 plays a key role in cell division and elongation, particularly enhancing root biomass and overall seedling establishment. The control treatment (T9), which involved only soil and no growth regulator, consistently showed the lowest performance across all parameters, including germination percentage (51.67%), seedling vigour (331.55), and survival percentage (77.58%), confirming the inadequacy of unamended soil and absence of growth-promoting substances for nursery-level papaya production. In conclusion, the study demonstrates that the integrated use of PGRs and a balanced growing medium significantly enhances papaya seed germination and seedling quality. For nursery managers and papaya growers, the combination of NAA @ 50 ppm with the soil + vermicompost + Perlite media mix (T4) is recommended for achieving superior germination and uniformity, while GA3 @ 50 ppm with the same media (T8) is ideal for enhancing root development and seedling vigour. These findings can serve as a practical guideline for improving the efficiency and success rate of papaya seedling production under nursery conditions.

Keywords: Papaya; plant growth regulators; gibberellic acid; naphthalene acetic acid; seed germination; seedling vigour and growing media.

1. Introduction

Papaya (*Carica papaya* L.) is one of the most important tropical fruit crops belonging to the family Caricaceae and is widely cultivated in tropical and subtropical regions of the world. It is commonly known as papaw or pawpaw and is recognized for its rapid growth, high productivity, early fruit bearing and excellent nutritional quality. Papaya is considered an economically important fruit crop because it requires comparatively less land, starts fruiting within one year after planting and provides high economic returns per unit area. Due to its adaptability and ease of cultivation, papaya has become an important component of commercial horticulture and contributes significantly to agricultural income and rural employment (Chadha, 1992). Papaya originated in the tropical lowlands of southern Mexico and Central America, particularly in regions comprising southern Mexico, Belize and northern Guatemala and Honduras (Chan & Paull, 2008; Storey, 1976). From its centre of origin, papaya spread throughout tropical and subtropical regions and is now cultivated extensively in countries such as India, Brazil, Indonesia, Nigeria, Malaysia, Sri Lanka, Bangladesh, South Africa, Australia and the Philippines. Because of favourable climatic conditions and increasing consumer demand, papaya cultivation has expanded considerably worldwide. Papaya is an herbaceous perennial plant characterized by a shallow fibrous root system and a single soft, hollow stem that supports rapid growth. The plant generally attains a height of 2–10 m and bears large palmately lobed leaves arranged spirally at the stem apex. Depending upon the cultivar, papaya plants may be dioecious, monoecious, or hermaphroditic (Arriola et al., 1980). Fruits develop from the leaf axils and vary in shape and size according to genotype and environmental conditions.

Papaya occupies a significant position among fruit crops because of its high productivity and commercial importance. It ranks among the leading tropical fruit crops globally and plays an important role in improving nutritional security and farmers' income. India is the largest producer of papaya in the world and contributes nearly 40 percent of total global production. According to Government of India statistics, papaya is cultivated over an area of approximately 1.49 lakh hectares with an annual production of nearly 59.49 lakh tonnes. Major papaya-producing states include Andhra Pradesh, Tamil Nadu, Karnataka, Maharashtra, Gujarat and West Bengal. The tropical climatic conditions of India permit year-round cultivation and multiple harvests, making papaya a highly profitable fruit crop. Despite the leading position in production, papaya productivity is affected by several constraints including poor seed germination, low-quality planting material, insufficient nutrient management, inadequate nursery techniques and environmental stresses (Paz & Vázquez-Yanes, 1998). Therefore, improving nursery management and seedling establishment is essential for achieving sustainable productivity.

Papaya is widely recognized as one of the most nutritious fruits due to its rich composition of vitamins, minerals, antioxidants and bioactive compounds. The fruit is low in calories and cholesterol-free, making it suitable for healthy dietary practices. Fresh ripe papaya contains approximately 43 calories per 100 g and provides essential nutrients required for human health (Koul et al., 2022). Papaya is an excellent source of vitamin C and provitamin A compounds including beta-carotene and beta-cryptoxanthin. It also contains folate and B-complex vitamins such as thiamine, riboflavin, niacin and pantothenic acid. Important minerals present in papaya include potassium, calcium, phosphorus, magnesium, iron, zinc and copper (Koul et al., 2022; Oloyede, 2005). Besides fresh consumption, papaya is used in preparation of jams, jellies, syrups, pickles, dehydrated products, baby foods and beverages. Traditionally, different parts of papaya have also been used for treating digestive disorders and improving general health (Koul et al., 2022).

Environmental conditions strongly influence papaya growth, seed germination and seedling establishment. Papaya grows best under warm tropical conditions with optimum temperatures ranging from 21–35°C and requires fertile, well-drained soils rich in organic matter. The crop is sensitive to frost and prolonged waterlogging. Modern papaya cultivation emphasizes scientific nursery management practices through the use of suitable growing media and plant growth regulators (PGRs). Growing media play an important role in providing support, moisture retention, aeration, nutrient availability and favourable root conditions (Abad et al., 2002). Different media components such as soil, vermicompost, cocopeat, perlite and vermiculite are commonly used for raising healthy seedlings. Cocopeat improves water retention and porosity, whereas vermicompost enhances nutrient availability and microbial activity (Gupta et al., 2014; Reddy et al., 2023).

Recent papaya studies have reported that composite media containing vermicompost, cocopeat and/or perlite can improve germination and early seedling growth relative to soil-based controls, although the magnitude of response varies with substrate composition (Krishnanayak et al., 2024; Kumar et al., 2024).

Plant growth regulators have gained considerable importance in improving seed germination and seedling development. Among them, Gibberellic Acid (GA_3) is effective in breaking seed dormancy, stimulating enzyme activity and promoting cell elongation, while Naphthalene Acetic Acid (NAA) enhances root initiation and seedling vigour (Desai et al., 2017; Raven et al., 2005; Sawada et al., 2008).

Seed priming can initiate controlled metabolic activity before radicle emergence and improve the speed and uniformity of subsequent germination; these responses are associated with interacting hormonal and redox pathways (Koushal et al., 2024; Wang et al., 2025). In papaya cv. Red Lady, the interaction between GA_3 concentration and growing-medium composition has also been shown to influence germination, seedling vigour and early growth (Kaur et al., 2026).

However, within the experimental context addressed by this manuscript, evidence directly comparing NAA and GA_3 at the same concentration across soil-based media containing vermicompost, cocopeat or perlite remains limited. Evaluating these combinations under a common nursery environment is therefore necessary to determine which treatments support both germination performance and balanced early seedling development.

The integrated use of growing media and plant growth regulators has shown significant potential for improving germination percentage, seedling growth, root development and survival of papaya seedlings. Therefore, the present investigation was undertaken to identify suitable combinations of growing media and plant growth regulators for optimizing seed germination and seedling growth in papaya (*Carica papaya* L.).

2. Material and Methods

The present investigation was conducted at the Horticulture Experimental Field, School of Advanced Agriculture Sciences and Technology, Chhatrapati Shahu Ji Maharaj University, Kanpur, Uttar Pradesh, during the year 2026. The experiment was carried out under nursery conditions to evaluate the effect of different growing media and plant growth regulators on seed germination and seedling growth of papaya. The experimental site is located at 26.4499° N latitude and 80.3319° E longitude, at an altitude of approximately 126 m above mean sea level. The region falls under the North Indo-Gangetic Plain (Zone IV) and experiences a semi-arid climate characterized by hot summers, moderate winters and seasonal monsoon rainfall. Annual rainfall in the region ranges between 800–1000 mm, with temperatures varying from 5°C during winter to above 40°C during summer. These climatic conditions are considered suitable for raising papaya seedlings under protected nursery conditions.

2.1 Experimental Design and Treatments

The experiment was laid out in a Complete Randomized Design (CRD) with nine treatments and three replications, comprising a total of 270 polybags (9 treatments × 30 polybags), with one seedling raised per polybag (10 polybags per replication). The nine treatments were as follows:

T1: NAA @ 50 ppm, Soil + Cocopeat (1:1)
T2: NAA @ 50 ppm, Soil + Vermicompost (1:1)
T3: NAA @ 50 ppm, Soil + Perlite (1:1)
T4: NAA @ 50 ppm, Soil + Vermicompost + Perlite (1:1:1)
T5: GA3 @ 50 ppm, Soil + Cocopeat (1:1)
T6: GA3 @ 50 ppm, Soil + Vermicompost (1:1)
T7: GA3 @ 50 ppm, Soil + Perlite (1:1)
T8: GA3 @ 50 ppm, Soil + Vermicompost + Perlite (1:1:1)
T9: Control (Soil alone)

2.2 Seed Material

F1 hybrid seeds of the papaya cultivar ‘Red Lady’ were procured from Kanpur, sealed in 5 g airtight polythene packaging. ‘Red Lady’ is a gynodioecious variety that yields good-quality, medium-sized fruits (1–2 kg) with orange-red flesh, and commences bearing approximately 10 months after planting.

2.3 Preparation of Plant Growth Regulator Solutions

Stock solutions of NAA @ 50 ppm and GA3 @ 50 ppm were prepared by dissolving 50 mg of NAA and 50 mg of GA3, respectively, in one litre of distilled water.

2.4 Seed Treatment and Sowing

Seeds were individually immersed in the respective NAA or GA3 solutions for 3 to 4 hours prior to sowing, as per the assigned treatment, and were subsequently shade-dried for about 2 hours before sowing. Untreated seeds served as the control (T9). Treated and untreated seeds (one seed per polybag) were sown in polybags measuring 20 × 10 cm, at a depth of approximately 10–15 mm, in the respective growing media.

2.5 Irrigation and Nursery Management

Polybags were irrigated immediately after sowing and were given light irrigation daily until seedling emergence. After emergence was complete, the polybags were lightly irrigated twice a day. Standard nursery management practices, including weeding and need-based plant-protection measures, were followed throughout to ensure healthy seedling development.

2.6 Observations Recorded

Growing media components (soil, cocopeat, vermicompost, perlite) were mixed thoroughly in the ratios specified above and filled into the nursery polybags before sowing. Observations related to germination attributes (imbibition period, speed of emergence, germination percentage, seedling vigour index and survival percentage) were recorded for the sown seeds. Seedling growth parameters, namely seedling height, number of leaves, leaf area and stem girth, were recorded at 30 and 45 days after sowing (DAS) on ten randomly selected, tagged seedlings per treatment. Number of roots, root length, fresh weight of shoot, fresh weight of root and shoot:root ratio were recorded once, at the time of transplanting (45 DAS).

2.7 Statistical Analysis

The data recorded during the experiment were statistically analysed using the Complete Randomized Design (CRD) as outlined by Fisher and Yates (1963). The significance of differences between treatment means was tested using the 'F' test, and the critical difference (CD) at the 5% level of significance was worked out following Gomez and Gomez (1984), using SEm(±) = $\sqrt{(EMS/r)}$ and CD (5%) = $\sqrt{2}$ × SEm(±) × 't' value at error degrees of freedom.

3. Results and Discussion

3.1 Growth Parameters

3.1.1 Seedling Height (cm)

The data illustrating the impact of different growing media and plant growth regulators on papaya seedling height at 30 and 45 days after sowing (DAS) are presented in Table 1. The results obtained at both intervals reveal that the treatments exerted a statistically significant effect on seedling growth dynamics. At 30 DAS, the tallest seedlings (10.44 cm) were recorded in T8 (GA3 @ 50 ppm, Soil + Vermicompost + Perlite, 1:1:1), followed closely by T4 (NAA @ 50 ppm, Soil + Vermicompost + Perlite, 1:1:1) with 10.11 cm, and T6 (GA3 @ 50 ppm, Soil + Vermicompost, 1:1) with 10.10 cm. The shortest seedlings were observed in the control (T9: Soil only), which recorded a height of 5.91 cm. At 45 DAS, the trend remained consistent, with T8 again recording the highest seedling height (15.01 cm), followed by T4 (14.10 cm) and T6 (13.44 cm). The lowest seedling height was again observed in the control (T9), at 9.18 cm.

These findings are in close agreement with Ramteke et al. (2015), who reported that a combination of soil, sand, cocopeat and vermicompost (1:1:1:1) with GA3 @ 200 ppm produced the greatest seedling height in papaya cv. Coorg Honey Dew, confirming the beneficial effect of multi-component growing media enriched with GA3 on shoot elongation. Similarly, Upadhyay et al. (2015) recorded the maximum seedling height of papaya cv. Madhu Bindu in a Soil + Cocopeat + Vermicompost + Sand (1:1:1:1) medium, supporting the present observation that composite, well-aerated growing media favour vertical seedling growth over single-component media or plain soil.

Table 1. Effect of growth media and plant growth regulators on Seedling Height (cm) of papaya

Treatment	Treatment Details	30 DAS	45 DAS
T1	NAA @50ppm, Soil + Cocopeat (1:1)	8.25	12.10
T2	NAA @50ppm, Soil + Vermicompost (1:1)	9.86	12.83
T3	NAA @50ppm, Soil + Perlite (1:1)	9.12	12.44
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	10.11	14.10
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	9.36	12.50
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	10.10	13.44
T7	GA3 @50ppm, Soil + Perlite (1:1)	9.36	12.80
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	10.44	15.01
T9	Control (Soil)	5.91	9.18
	C.D. @ 5%	0.65	0.65
	S.Em. (±)	0.22	0.21

3.1.2 Number of Leaves Per Plant

The data reflecting the influence of different growing media and plant growth regulators on leaf count in papaya seedlings at 30 and 45 DAS are presented in Table 2. Statistical analysis indicates that the number of leaves per seedling was significantly affected by both the growing medium and the applied plant growth regulator. At 30 DAS, the number of leaves per plant ranged from 5.14 to 7.45, with the maximum (7.45) recorded in T8, followed by T4 (7.10), T6 (6.80) and T2 (6.45). The lowest number of leaves was recorded in the control (T9), with 4.40 leaves per plant. At 45 DAS, values ranged from 6.95 to 9.25, with the highest again recorded in T8 (9.25), followed by T4 (9.10) and T6 (8.65); T2, T3, T5 and T7 showed intermediate values, while the lowest value was again recorded in the control (T9), with 6.44 leaves per plant.

A comparable trend was reported by Anjanawe et al. (2013) in papaya cv. Barwani Red, where GA3 at 200 ppm, followed by NAA at 50 ppm, produced the greatest vegetative growth including leaf development, supporting the present finding that PGR-enriched composite media favour leaf production over untreated soil.

Table 2. Effect of growth media and plant growth regulators on Number of Leaves per plant of papaya

Treatment	Treatment Details	30 DAS	45 DAS
T1	NAA @50ppm, Soil + Cocopeat (1:1)	5.14	6.95
T2	NAA @50ppm, Soil + Vermicompost (1:1)	6.45	8.44
T3	NAA @50ppm, Soil + Perlite (1:1)	6.10	8.45
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	7.10	9.10
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	6.25	8.14
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	6.80	8.65
T7	GA3 @50ppm, Soil + Perlite (1:1)	5.40	7.30
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	7.45	9.25
T9	Control (Soil)	4.40	6.44
	C.D. @ 5%	0.55	0.54
	S.Em. (±)	0.18	0.18

3.1.3 Leaf Area (cm²)

The data on the effect of different growing media and plant growth regulators on leaf area of papaya seedlings are presented in Table 3. Statistical analysis showed that both the growing medium and the plant growth regulator had a significant impact on leaf area expansion. At 30 DAS, leaf area ranged between 14.62 cm² and 18.91 cm², with the highest value recorded in T8 (18.91 cm²), followed by T4 (18.15 cm²) and T6 (17.92 cm²); the lowest (14.62 cm²) was recorded in the control (T9). At 45 DAS, leaf area ranged from 26.58 cm² to 34.37 cm², with T8 again recording the highest value (34.37 cm²), followed by T4 (33.01 cm²) and T6 (32.59 cm²); the control (T9) again recorded the lowest value (26.58 cm²). Leaf area increased with seedling age across all treatments, and combinations involving multiple growing-media components consistently recorded higher leaf area at both growth stages.

This is in line with Kumararvind et al. (2015), who found that a Soil + Sand + Vermicompost (1:1:1) medium gave significantly greater seedling vigour and leaf development in papaya nursery seedlings compared with simpler media, reinforcing the present observation that nutrient-rich, multi-component substrates enhance photosynthetic leaf area more effectively than single-component media.

Table 3. Effect of growth media and plant growth regulators on Leaf Area (cm²) of papaya

Treatment	Treatment Details	30 DAS	45 DAS
T1	NAA @50ppm, Soil + Cocopeat (1:1)	16.18	29.41
T2	NAA @50ppm, Soil + Vermicompost (1:1)	17.34	31.52
T3	NAA @50ppm, Soil + Perlite (1:1)	16.71	30.37
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	18.15	33.01
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	16.97	30.84
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	17.92	32.59
T7	GA3 @50ppm, Soil + Perlite (1:1)	17.40	31.64
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	18.91	34.37
T9	Control (Soil)	14.62	26.58
	C.D. @ 5%	1.26	2.29
	S.Em. (±)	0.42	0.76

3.1.4 Stem Girth (mm)

Data on the influence of different growing media and plant growth regulators on the stem girth of papaya seedlings at 30 and 45 DAS are presented in Table 4. The findings reveal that both the growing media and the plant growth regulator significantly affected stem girth development. At 30 DAS, stem girth values ranged from 3.11 mm to 3.94 mm. The highest stem girth (3.94 mm) was recorded in T8, followed by T4 (3.83 mm) and T6 (3.79 mm). T2, T5 and T7 recorded intermediate values (3.67–3.72 mm), while T1 and T3 recorded slightly lower values (3.52 mm and 3.54 mm, respectively). The lowest stem girth (3.11 mm) was recorded in the control (T9). At 45 DAS, stem girth ranged from 4.01 mm to 5.58 mm. T8 again recorded the maximum (5.58 mm), followed by T6 (5.44 mm) and T5/T7 (5.25/5.11 mm). T4 recorded 5.06 mm, T2 recorded 4.08 mm and T1 recorded 4.44 mm, while T3 was slightly lower at 4.15 mm. The lowest stem girth (4.01 mm) was again recorded in the control (T9).

Table 4. Effect of growth media and plant growth regulators on Stem Girth (mm) of papaya

Treatment	Treatment Details	30 DAS	45 DAS
T1	NAA @50ppm, Soil + Cocopeat (1:1)	3.52	4.44
T2	NAA @50ppm, Soil + Vermicompost (1:1)	3.72	4.08
T3	NAA @50ppm, Soil + Perlite (1:1)	3.54	4.15
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	3.83	5.06
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	3.64	5.25
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	3.79	5.44
T7	GA3 @50ppm, Soil + Perlite (1:1)	3.67	5.11
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	3.94	5.58
T9	Control (Soil)	3.11	4.01
	C.D. @ 5%	0.21	0.48
	S.Em. (±)	0.073	0.16

This finding corroborates Mirza et al. (2019), who reported that GA3 @ 200 ppm significantly enhanced stem diameter along with plant height in papaya cv. Taiwan Red Lady, supporting the present observation that GA3-based treatments, particularly when combined with a nutrient-rich composite medium, favour stem thickening in papaya seedlings.

3.1.5 Number of Roots and Root Length (cm)

The data regarding the effect of different growing media and plant growth regulators on the number of roots and root length of papaya seedlings at 45 DAS are presented in Table 5. The results revealed that both the plant growth regulator and the growing medium significantly influenced root number and root length. The highest number of roots (19.05) was recorded in T8, followed by T4 (18.57), T6 (18.04) and T7 (18.03). T5 recorded 17.05 roots and T2 recorded 16.95 roots, while T1 and T3, involving NAA with cocopeat and Perlite respectively, recorded 16.11 and 15.10 roots. The lowest number of roots (15.04) was recorded in the control (T9). Root length followed a similar pattern: the maximum (11.35 cm) was recorded in T8, followed by T4 and T2 (10.36 cm each) and T6 (10.30 cm). T5 and T7 recorded 9.60 cm and 9.25 cm, respectively, while T3 and T1 recorded 9.13 cm and 8.44 cm. The lowest root length (6.25 cm) was recorded in the control (T9).

This observation is consistent with Sharma et al. (2018), who reported that NAA treatment of papaya cv. Pusa Nanha seeds increased auxin levels in the roots, resulting in additional root initiation, root cell elongation and greater tap-root and root numbers, thereby supporting the present finding that NAA-based treatments (T1–T4) promoted comparatively vigorous root systems alongside the GA3-based treatments.

3.1.6 Fresh Weight of Shoot, Fresh Weight of Root, and Shoot:Root Ratio

The data regarding the effect of different growing media and plant growth regulators on the fresh weight of shoot, fresh weight of root, and shoot:root ratio of papaya seedlings at 45 DAS are presented in Table 6. The highest fresh shoot weight (4.21 g) was recorded in T8 (GA3 @ 50 ppm, Soil + Vermicompost + Perlite), followed by T6 (3.81 g), T7 (3.65 g) and T2 (3.62 g). Moderate shoot weights were recorded in T5 (3.55 g) and T1 (3.34 g), while T3 (3.28 g) and T4 (3.09 g) recorded comparatively lower shoot weights. The lowest shoot weight (2.04 g) was recorded in the control (T9), confirming the effectiveness of growth regulators and enriched media in improving shoot biomass.

Table 5. Effect of growth media and plant growth regulators on Number of Roots and Root Length (cm) of papaya

Treatment	Treatment Details	No. of Roots	Root Length (cm)
T1	NAA @50ppm, Soil + Cocopeat (1:1)	16.11	8.44
T2	NAA @50ppm, Soil + Vermicompost (1:1)	16.95	10.36
T3	NAA @50ppm, Soil + Perlite (1:1)	15.10	9.13
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	18.57	10.36
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	17.05	9.60
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	18.04	10.30
T7	GA3 @50ppm, Soil + Perlite (1:1)	18.03	9.25
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	19.05	11.35
T9	Control (Soil)	15.04	6.25
	C.D. @ 5%	0.66	0.51
	S.Em. (±)	0.22	0.17

The highest fresh root weight (1.14 g) was recorded in Treatment T8 (GA3 @ 50 ppm with soil, vermicompost and Perlite), followed by T4 (1.10 g) and T6 (0.93 g). Moderate root weights were observed in T2 (0.82 g), T5 (0.81 g), T1 and T7 (0.75 g each), and T3 (0.71 g). The lowest root weight (0.07 g) was recorded in the control (T9), highlighting the benefit of combining growth regulators with enriched growing media for root biomass accumulation.

Table 6. Effect of growth media and plant growth regulators on Fresh Weight of Shoot (g), Fresh Weight of Root (g), and Shoot:Root Ratio of papaya

Treatment	Treatment Details	Fresh Wt. Shoot (g)	Fresh Wt. Root (g)	Shoot:Root Ratio
T1	NAA @50ppm, Soil + Cocopeat (1:1)	3.34	0.75	4.45
T2	NAA @50ppm, Soil + Vermicompost (1:1)	3.62	0.82	4.31
T3	NAA @50ppm, Soil + Perlite (1:1)	3.28	0.71	4.62
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	3.09	1.10	3.55
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	3.55	0.81	4.38
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	3.81	0.93	3.97
T7	GA3 @50ppm, Soil + Perlite (1:1)	3.65	0.75	4.87
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	4.21	1.14	3.73
T9	Control (Soil)	2.04	0.07	2.91
	C.D. @ 5%	0.27	0.085	0.26
	S.Em. (±)	0.09	0.02	0.08

The shoot:root ratio, which reflects the balance between above-ground and below-ground biomass, was significantly influenced by the treatments. Contrary to the impression that the treatments with the greatest absolute shoot and root biomass (T8 and T4) also had the highest shoot:root ratio, the data in Table 6 show that the highest shoot:root ratio (4.87) was in fact recorded in Treatment T7 (GA3 @ 50 ppm, Soil + Perlite), followed by T3 (4.62), T1 (4.45), T5 (4.38) and T2 (4.31). Treatments T6 (3.97), T8 (3.73) and T4 (3.55) recorded comparatively lower shoot:root ratios, despite T8 and T4 recording the highest absolute shoot and root weights; this pattern indicates that, in T8 and T4, biomass was proportionately allocated more toward root development relative to shoot growth, rather than these treatments having the highest shoot-dominant ratio. The lowest shoot:root ratio (2.91) was recorded in the control (T9), where seedlings were raised in plain soil without any plant growth regulator, reflecting weak shoot development relative to root growth. Overall, the results indicate that growth regulators and enriched growing media influenced shoot and root partitioning differently depending on the specific medium composition used, rather than uniformly raising the shoot:root ratio in the treatments with the highest total biomass.

These results are broadly supported by Kumawat et al. (2014), who found that a soil, compost and cocopeat (1:1:1) medium combined with GA3 @ 150 ppm promoted superior shoot and tap-root development along with increased secondary root formation in papaya cv. Coorg Honey Dew, and by Mandal et al. (2015), who reported that a similar composite medium with GA3 @ 500 ppm significantly enhanced overall growth parameters of papaya seedlings, consistent with the superior shoot and root biomass recorded in the composite-medium treatments (T4 and T8) of the present study.

3.2 Germination Parameters

The germination-related dataset presented in this section imbibition period, speed of emergence, germination percentage, seedling vigour index and survival percentage was not present in the originally submitted manuscript. This section, together with Tables 7 and 8 below, has now been incorporated from the underlying approved thesis on which the manuscript is based, so that the Results and Discussion chapter reports the complete set of parameters described in the Abstract and Materials and Methods.

3.2.1 Imbibition Period and 4.2.2 Speed of Emergence

The imbibition period (days from sowing to the commencement of germination) and the speed of emergence were both significantly influenced by the plant growth regulator and the growing medium (Table 7). The shortest imbibition period (7.67 days) was recorded in T1 (NAA @ 50 ppm, Soil + Cocopeat), followed closely by T2 (8.47 days), T3 (8.69 days) and T4 (9.00 days) all NAA-based treatments indicating that NAA effectively promoted early water uptake, likely through enhanced seed-coat permeability and activation of hydrolytic enzymes. Among the GA3-based treatments, T5 recorded the shortest imbibition period (9.33 days), followed by T6 (11.31 days), T7 (11.44 days) and T8 (12.02 days). The control (T9), with no growth regulator, recorded the longest imbibition period (15.78 days).

The speed of emergence was highest in T4 (92.12), followed by T2 (91.01), T3 (90.26) and T1 (90.01) again, all NAA-based treatments suggesting a synergistic effect between NAA and well-aerated, moisture-retentive media in accelerating seedling emergence. Among the GA3 treatments, T6 recorded the highest emergence speed (89.76), followed by T5 (76.44), T8 (73.35) and T7 (72.45, the lowest among the GA3 treatments). The control (T9) recorded the lowest speed of emergence overall (59.15), underlining the importance of plant growth regulators, and particularly NAA, in promoting rapid and uniform seedling emergence.

Table 7. Effect of growth media and plant growth regulators on Imbibition Period (days) and Speed of Emergence of papaya

Treatment	Treatment Details	Imbibition Period (days)	Speed of Emergence
T1	NAA @50ppm, Soil + Cocopeat (1:1)	7.67	90.01
T2	NAA @50ppm, Soil + Vermicompost (1:1)	8.47	91.01
T3	NAA @50ppm, Soil + Perlite (1:1)	8.69	90.26
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	9.00	92.12
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	9.33	76.44
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	11.31	89.76
T7	GA3 @50ppm, Soil + Perlite (1:1)	11.44	72.45
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	12.02	73.35
T9	Control (Soil)	15.78	59.15
	C.D. @ 5%	0.48	1.31
	S.Em. (±)	0.16	0.43

These trends are consistent with Bhardwaj (2013), who reported that a vermicompost + sand + pond soil (1:1:1) medium with a surface cocopeat layer produced the highest speed of seedling emergence, highest germination percentage, highest seed vigour and the least time for imbibition in papaya cv. Red Lady, corroborating the present finding that enriched, well-aerated composite media shorten the imbibition period and accelerate emergence relative to plain soil.

3.2.2 Germination Percentage, 4.2.4 Seedling Vigour Index, and 4.2.5 Survival Percentage

Germination percentage, seedling vigour index and survival percentage are presented in Table 8. Germination percentage ranged from 50.11% (control, T9) to 73.13% (T4). NAA-based treatments (T1–T4) consistently recorded higher germination percentages (66.44–73.13%) than GA3-based treatments (T5–T8, 51.45–61.13%), with T4 and T2 recording the highest values (73.13% each), followed by T3 (70.18%) and T1 (66.44%). Among the GA3 treatments, T5 recorded the highest germination percentage (61.13%), followed by T6 (56.11%), T8 (54.10%) and T7 (51.45%, the lowest among the GA3 treatments).

Seedling vigour index followed a similar trend, with the highest value recorded in T4 (763.47), followed by T2 (738.92), T3 (709.51) and T1 (655.09). Among the GA3 treatments, T8 recorded the highest vigour index (576.17), followed by T6 (512.84), T7 (446.32) and T5 (417.25). The lowest seedling vigour index (308.17) was recorded in the control (T9).

Survival percentage was highest in T4 (96.14%), followed by T8 (94.25%), T2 (91.16%), T3 (90.80%), T1 (86.14%), T6 (84.54%), T5 (83.33%) and T7 (81.11%). The lowest survival percentage (75.44%) was recorded in the control (T9). Taken together, these germination parameters indicate that NAA @ 50 ppm, particularly in combination with the soil + vermicompost + Perlite medium (T4), was most effective in promoting rapid, uniform germination, high seedling vigour and superior survival, while GA3 @ 50 ppm in the same medium (T8) was comparatively more effective for vegetative and root growth, as discussed in Section 4.1.

Table 8. Effect of growth media and plant growth regulators on Germination Percentage, Seedling Vigour Index and Survival Percentage of papaya

Treatment	Treatment Details	Germination (%)	Seedling Vigour Index	Survival (%)
T1	NAA @50ppm, Soil + Cocopeat (1:1)	66.44	655.09	86.14
T2	NAA @50ppm, Soil + Vermicompost (1:1)	73.13	738.92	91.16
T3	NAA @50ppm, Soil + Perlite (1:1)	70.18	709.51	90.80
T4	NAA @50ppm, Soil + Vermicompost + Perlite (1:1:1)	73.13	763.47	96.14
T5	GA3 @50ppm, Soil + Cocopeat (1:1)	61.13	417.25	83.33
T6	GA3 @50ppm, Soil + Vermicompost (1:1)	56.11	512.84	84.54
T7	GA3 @50ppm, Soil + Perlite (1:1)	51.45	446.32	81.11
T8	GA3 @50ppm, Soil + Vermicompost + Perlite (1:1:1)	54.10	576.17	94.25
T9	Control (Soil)	50.11	308.17	75.44
	C.D. @ 5%	1.50	6.462	1.146
	S.Em. (±)	0.50	2.158	0.383

These results align with several earlier reports on papaya seed germination. Deb et al. (2010) found that GA3 @ 150 ppm produced the highest seed germination percentage in papaya, while GA3 @ 200 ppm maximised seedling height and girth, illustrating the same general concentration-dependent response to GA3 observed for the vegetative parameters in the present study. Hossain et al. (2023) similarly reported that GA_3 seed priming combined with a medium containing soil, cocopeat and vermicompost increased papaya seed germination and seedling growth, supporting the comparatively favourable response of the GA_3-based treatments in the present study relative to the control. More recently, Abhishek et al. (2024) reported that GA3 @ 150 ppm and NAA @ 150 ppm both significantly improved germination percentage, seedling vigour and survival percentage of papaya compared with untreated control seedlings, which is in agreement with the markedly higher germination, vigour and survival values recorded for all PGR-based treatments (T1–T8) relative to the control (T9) in the present investigation.

4. Conclusion

The study concluded that the application of plant growth regulators along with an improved growing medium significantly enhanced papaya seed germination and seedling growth under nursery conditions. NAA @ 50 ppm proved highly effective in reducing the imbibition period, accelerating seed emergence, and improving germination percentage, seedling vigour and survival percentage, particularly when combined with the growing medium containing soil, vermicompost, and Perlite in equal proportions (T4). GA_3 @ 50 ppm showed superior performance in promoting vegetative growth and root development — including seedling height, leaf number, leaf area, stem girth, root number and length, and fresh shoot and root weight — with Treatment T8 (the same soil + vermicompost + Perlite medium) producing the strongest vegetative and root development, although its shoot:root ratio was comparatively lower than several other treatments, reflecting a proportionately greater allocation of biomass to root growth. The balanced growing medium of soil, vermicompost, and Perlite created favourable conditions through improved aeration, moisture retention, and nutrient availability, contributing to enhanced germination and seedling establishment in both PGR treatments. In contrast, the control treatment using soil alone recorded the poorest performance across all growth and germination parameters, indicating that plain soil is inadequate for quality papaya seedling production. Therefore, for successful nursery management and production of healthy, vigorous papaya seedlings, the combined use of NAA @ 50 ppm or GA_3 @ 50 ppm with the soil + vermicompost + Perlite growing medium is recommended, with the choice between the two depending on whether rapid, uniform germination and survival (NAA, T4) or vegetative and root growth (GA_3, T8) is the primary nursery objective.

5. Limitation

This study was conducted at a single location during one season, using one papaya cultivar and a single concentration (50 ppm) of each plant growth regulator. Seedlings were evaluated only up to 45 days after sowing under nursery conditions. Therefore, the findings do not establish whether the observed treatment responses persist after transplanting or under different climates, cultivars, regulator concentrations, or commercial nursery systems. Physiological and biochemical mechanisms underlying the treatment responses were not directly measured.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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