



Comparative Evaluation of Germination Behaviour and Early Seedling Growth of F₁ Progenies in Custard Apple (*Annona squamosa* L.) under the South Saurashtra Agro-climatic Zone of Gujarat, India

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Authors' contributions

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

Article Information

DOI: <https://doi.org/10.9734/ijpss/2026/v38i106387>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://pr.sdiarticle5.com/review-history/164753>

Original Research Article

Received: 30/05/2026

Accepted: 17/08/2026

Published: 24/10/2026

Abstract

Custard apple (*Annona squamosa* L.) breeding requires early evaluation of progenies to identify cross combinations with favourable germination and seedling growth. The present investigation evaluated 20 F₁ cross combinations involving Selection No. 11, Balanagar, Sindhan, Mammoth and GJCA-1 under shade-net nursery conditions at Junagadh Agricultural University, Gujarat, from February to May 2025. The experiment was conducted in a Randomised Block Design with three replications, using 20 seeds per cross combination in each replication. Germination percentage was assessed at 30 days after sowing, and plant height, stem diameter, leaf length and leaf width were recorded at 90 days after sowing. Significant differences were observed among the cross combinations for germination behaviour and early seedling growth. Balanagar × Sindhan (C₆) recorded the earliest emergence (22.66 days) and the highest germination percentage (86.92%). Selection 11 × GJCA-1 (C₄) produced the

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greatest plant height (30.65 cm) and stem diameter (3.70 mm), whereas GJCA-1 × Mammoth (C₂₀) recorded the greatest leaf length (8.72 cm) and leaf width (3.32 cm). Reciprocal combinations showed contrasting performance for several traits, although maternal, paternal and cytoplasmic effects were not separately evaluated. The observed trait-specific variation indicates that multiple cross combinations should be considered during early progeny evaluation. The identified progenies provide material for subsequent nursery and field assessment at later growth stages.

Keywords: *Annona squamosa*; custard apple; *F₁* progenies, genotypes; seed germination; seedling vigour.

1. Introduction

Custard apple (*Annona squamosa* L.) is an important fruit crop of tropical and subtropical regions and is well adapted to dry and semi-arid environments because of its hardy nature and comparatively low input requirements. In India, the crop is cultivated under diverse agro-climatic conditions and has considerable economic importance, particularly in regions where its adaptability favours cultivation under relatively low-input production systems (Leal & Paull, 2023).

The fruit is nutritionally valuable and contains appreciable quantities of sugars, proteins, minerals, vitamins and other nutrients and is consumed fresh as well as processed into pulp for ice creams, milkshakes, custards and other products (Kumar et al., 2021).

Different plant parts have also been traditionally utilised for medicinal purposes in Ayurvedic and Unani systems (Anaya-Esparza et al., 2020). Despite its economic importance, the productivity of custard apple remains relatively low, primarily because of poor and irregular fruit set. The crop is characterised by protogynous dichogamy, in which stigma receptivity precedes anther dehiscence, thereby favouring cross-pollination and making effective pollen transfer essential for successful fertilisation (Saunders, 2020).

Limited pollinator activity, inadequate pollen deposition and environmental conditions during flowering may further reduce effective pollination and fruit set (Chagas et al., 2022; Mendes et al., 2012).

The limited availability of improved cultivars and the considerable variation among *F₁* progenies within *Annona* provide opportunities for crop improvement through hybridisation (Prasad et al., 2025). Hybridisation is an important breeding approach for combining desirable attributes from genetically diverse parents and generating new recombinants. In *Annona*, both interspecific and intraspecific hybridisation have been utilised to exploit available genetic diversity and develop superior types. The development of the hybrid 'Arka Sahan', derived from *A. cherimola* × *A. squamosa* followed by crossing with *A. squamosa*, demonstrates the potential of hybridisation for combining desirable fruit characteristics in *Annona*. Furthermore, studies involving interspecific *Annona* progenies have demonstrated substantial variation among progenies for tree and fruit characteristics, indicating the usefulness of hybrid populations for identifying desirable recombinants (Jalilop, 2010; Rajpoot et al., 2026). A recent review of horticultural crop improvement describes conventional hybridisation and selection as established breeding approaches that are increasingly integrated with molecular methods (Raghavan et al., 2025).

F₁ progenies constitute the first generation obtained from selected parental combinations and provide an opportunity to assess the expression of recombined parental characteristics. The use of genetically diverse parents can generate phenotypic variation among progenies, thereby providing opportunities for identifying selected individuals for subsequent breeding programmes (Prasad et al., 2025). Recent characterisation of *A. squamosa* germplasm has also demonstrated substantial agro-morphological variability among genotypes, reinforcing the potential for genetic improvement through appropriate selection and hybridisation (Nogueira et al., 2022). A recent high-quality genome assembly of *A. squamosa* provides a genomic resource that may support future investigations of genetic variation and crop improvement in the species (Bisht et al., 2025).

Evaluation of *F₁* progenies at the seedling stage is an important preliminary step in a breeding programme because early germination and vegetative growth provide useful information for identifying *F₁* progenies with comparatively better early growth performance.

Seed germination in *A. squamosa* is influenced by seed characteristics and physiological conditions, and considerable attention has been given to improving germination and subsequent seedling growth through seed treatments (Mimi et al., 2023). Studies in custard apple have demonstrated significant variation in days to first plumule emergence, germination percentage, seedling height, stem diameter, number of leaves, leaf area, fresh and dry biomass and seedling vigour, indicating that these traits are useful indicators of early seedling performance (Singour et al., 2023). Recent shade-net research in custard apple similarly reported that pre-sowing treatments can influence both seed germination and early shoot growth, supporting the sensitivity of nursery-stage performance to seed treatment (Priyanka et al., 2025).

Early vegetative characters such as plant height, stem diameter and leaf development are particularly useful for assessing seedling vigour because they reflect the establishment and growth potential of young plants. Variation in these characters has been reported in custard apple seedlings subjected to different growing conditions and pre-sowing treatments, suggesting that early growth characteristics can be effectively used to discriminate among seedlings and identify selected planting material. More recent investigations have similarly reported significant differences among custard apple seedlings for germination percentage, seedling height, stem diameter, number of leaves and other growth attributes (Deeksha et al., 2023). Recent comparative work in *Annona* has also incorporated germination and juvenile growth traits in the assessment of early growth differences, indicating the continued utility of such characters for seedling-stage evaluation (Okechukwu et al., 2025).

Although several studies have examined seed treatments and their influence on germination and seedling growth in custard apple, relatively limited information is available on the comparative performance of *F₁* progenies derived from different parental cross

combinations. Evaluation of F_1 progenies for germination behaviour and early vegetative growth can therefore provide useful information for identifying cross combinations with selected seedling performance. Such information is particularly valuable in breeding programmes where early selection can help narrow the population for subsequent field evaluation. The use of diverse *Annona* parents and evaluation of their progenies has previously demonstrated the potential to generate considerable variation for selection and genetic improvement (Sushmitha & Sakthivel, 2023).

Therefore, the present investigation was undertaken to evaluate twenty F_1 cross combinations of custard apple (*Annona squamosa* L.) for germination behaviour and early seedling growth based on days to first emergence, germination percentage, plant height, stem diameter, leaf length and leaf width, and to compare their performance for these early seedling traits.

2. Materials and Methods

2.1 Experimental Site

The investigation was conducted at the Department of Fruit Science, Fruit Research Station, Madhadi Baug, College of Horticulture, Junagadh Agricultural University (JAU), Junagadh, Gujarat. The experimental site is located in the Saurashtra zone at 21°30'56" N latitude and 70°27'23" E longitude, at an elevation of approximately 107 m above mean sea level. The region experiences a tropical to subtropical climate and the experimental site is characterised by medium to heavy black soil (Vertisols).

2.2 Plant Material

Twenty reciprocal cross combinations involving five custard apple parental genotypes, viz., Selection No. 11, Balanagar, Sindhan, Mammoth and GJCA-1, were generated through controlled hand pollination. Approximately 25 flowers were pollinated for each cross combination. The selected flowers were emasculated in the morning before anthesis to prevent self-pollination. Pollen was collected separately from flowers that had opened on the preceding day and transferred into clean plastic cups. Separate cups and brushes were used for each pollen source to minimise cross-contamination. The collected pollen was manually applied to the stigma of the emasculated flowers at the female receptive stage before anthesis using a clean, dry paintbrush. Each hand-pollinated flower was labelled with the pollen source and date of pollination. Approximately three fruits were obtained from each cross combination.

Seeds extracted from the fruits of each cross combination were pooled separately and the pooled seeds were subsequently used for the germination and early seedling growth study.

2.3 Seed Preparation and Sowing

Seeds obtained from each F_1 cross combination were soaked in water overnight before sowing. For each cross combination, 20 seeds were sown individually in each replication on 20 February 2025, with one seed placed in each 5 × 7-inch polythene bag containing soil as the growing medium. Thus, 20 seeds were sown per cross combination in each replication, resulting in a total of 60 seeds per cross combination across three replications. The seedlings were maintained under shade-net conditions and irrigated regularly three times a week using a rose can.

2.4 Experimental Design and Nursery Management

The experiment comprised 20 F_1 cross combinations and was laid out in a Randomised Block Design (RBD) with three replications.

Each cross combination constituted one treatment, with 20 seeds sown individually in separate 5 × 7-inch polythene bags in each replication. Thus, each cross combination was represented by 20 individually sown seeds per replication, giving a total of 60 seeds across the three replications. The seeds used for each cross combination were obtained by pooling seeds from approximately three fruits of the respective cross. The seedlings were maintained under uniform nursery and cultural conditions throughout the experimental period.

2.5 Assessment of Germination

Germination was monitored daily from the date of sowing. Emergence of the plumule was considered the criterion for germination.

The number of days to first emergence of the plumule in each replication was recorded and calculated as the interval between the date of sowing and the date of emergence of the first plumule in each replication. Final germination percentage was recorded at 30 days after sowing (DAS) and calculated as the percentage of seeds germinated relative to the total number of seeds sown.

2.6 Assessment of Seedling Growth

Seedling growth observations were recorded at 90 DAS. Five seedlings were randomly selected from each replication for recording seedling growth parameters, and the mean of the selected seedlings was used as the replication-wise observation for statistical analysis. Plant height was measured from the soil surface to the apical growing point of the selected seedling using a measuring scale and expressed in centimetres (cm). Stem diameter was measured at approximately 3 cm above the base of the stem using a vernier calliper and expressed in millimetres (mm). Leaf length was measured from the point of attachment of the leaf blade with the petiole to the tip of the lamina using a measuring scale. Leaf width was measured perpendicular to the midrib at the widest portion of the leaf lamina. Leaf length and leaf width were expressed in centimetres (cm).

2.7 Statistical Analysis

The data recorded for days to first emergence, germination percentage, plant height, stem diameter, leaf length and leaf width were subjected to an analysis of variance appropriate for a Randomised Block Design. The significance of differences among treatment means was tested using the F-test at the 5% probability level. Where the treatment effect was significant, the treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% level of significance. The standard error of the mean (SEm $\pm$), critical difference (CD) and coefficient of variation (CV) were calculated following the procedure described by Panse and Sukhatme (1985).

3. Results and Discussion

3.1 Germination Parameters

Significant differences (Table 1) among the F₁ cross combinations were observed for germination behaviour.

3.1.1 Days to First Emergence

The minimum number of days to first emergence (22.66 days) was recorded in Balanagar $\times$ Sindhan (C₆), which remained statistically at par with Sindhan $\times$ Selection 11 (C₉), Mammoth $\times$ Balanagar (C₁₄) and Sindhan $\times$ Mammoth (C₁₁). In contrast, the maximum number of days to first emergence (28.33 days) was recorded in Selection 11 $\times$ Mammoth (C₃). The reciprocal combinations showed contrasting performance for early emergence. Balanagar $\times$ Sindhan (C₆) recorded fewer days to first emergence than its reciprocal Sindhan $\times$ Balanagar (C₁₀) (22.66 vs. 25.17 days), while Mammoth $\times$ Selection 11 (C₁₃) emerged earlier than Selection 11 $\times$ Mammoth (C₃) (26.67 vs. 28.33 days). Such differences indicate that cross direction may influence early emergence behaviour in F₁ progenies, although the present experiment did not specifically test maternal or reciprocal effects.

Variation in emergence time may also be associated with differences in seed developmental characteristics and physiological quality among progenies (Singour et al., 2023).

3.1.2 Germination Percentage

The maximum germination percentage (86.92%) was recorded in Balanagar $\times$ Sindhan (C₆), which was statistically at par with Balanagar $\times$ GJCA-1 (C₈), whereas the minimum germination percentage (57.51%) was recorded in Selection 11 $\times$ Balanagar (C₁).

Marked differences were observed between several reciprocal combinations. Balanagar $\times$ Sindhan (C₆) recorded higher germination than its reciprocal Sindhan $\times$ Balanagar (C₁₀) (86.92 vs. 71.66%), while Balanagar $\times$ Selection 11 (C₅) showed higher germination than Selection 11 $\times$ Balanagar (C₁) (70.03 vs. 57.51%). Similarly, Mammoth $\times$ Selection 11 (C₁₃) recorded higher germination (79.64%) than Selection 11 $\times$ Mammoth (C₃) (58.29%). These contrasting performances suggest a possible influence of cross direction on germination performance in F₁ progenies; however, maternal, paternal and cytoplasmic effects were not separately evaluated in the present experiment. The observed variation may also be associated with differences in seed development and physiological quality among the progenies (Dadhaniya et al., 2020; Gharge et al., 2022).

3.2 Early Seedling Growth Parameters

Significant differences were observed among the 20 F₁ cross combinations (Table 1) for early seedling growth parameters.

3.2.1 Plant Height

The maximum plant height (30.65 cm) was recorded in Selection 11 $\times$ GJCA-1 (C₄), which was statistically at par with Mammoth $\times$ Balanagar (C₁₄) and GJCA-1 $\times$ Mammoth (C₂₀), whereas the minimum plant height (16.40 cm) was recorded in Sindhan $\times$ Mammoth (C₁₁). Contrasting performance was observed among several reciprocal combinations. Selection 11 $\times$ GJCA-1 (C₄) produced taller seedlings than its reciprocal GJCA-1 $\times$ Selection 11 (C₁₇) (30.65 vs. 24.36 cm), while Mammoth $\times$ Balanagar (C₁₄) recorded greater plant height than its reciprocal Balanagar $\times$ Mammoth (C₇) (30.46 vs. 23.97 cm). Similarly, GJCA-1 $\times$ Mammoth (C₂₀) produced taller seedlings than Mammoth $\times$ GJCA-1 (C₁₆) (30.42 vs. 23.58 cm). These contrasting performances suggest that cross direction may be associated with differences in early vegetative growth, although maternal, paternal and cytoplasmic effects were not separately evaluated in the present experiment. The observed variation in plant height indicates differential early growth performance among the F₁ progenies. Similar variation in seedling height has been reported in custard apple under different seed treatments and growing conditions (Sahu & Rana, 2024). Similar variation in plant height has been reported in jackfruit (Tippannavar & Singh, 2023).

3.2.2 Stem Diameter

Significant differences were observed among the F₁ cross combinations for stem diameter (Table 1). The maximum stem diameter (3.70 mm) was recorded in Selection 11 $\times$ GJCA-1 (C₄), which was statistically at par with Selection 11 $\times$ Mammoth (C₃), whereas the minimum stem diameter (2.45 mm) was recorded in GJCA-1 $\times$ Balanagar (C₁₈). Contrasting performance was observed among several reciprocal combinations. Selection 11 $\times$ GJCA-1 (C₄) recorded greater stem diameter than its reciprocal GJCA-1 $\times$ Selection 11 (C₁₇) (3.70 vs. 3.20 mm), while Selection 11 $\times$ Mammoth (C₃) recorded greater stem diameter than its reciprocal Mammoth $\times$

Selection 11 (C₁₃) (3.66 vs. 2.86 mm). Similarly, Sindhan × Balanagar (C₁₀) recorded greater stem diameter than its reciprocal Balanagar × Sindhan (C₆) (3.37 vs. 2.67 mm). These contrasting performances suggest that cross direction may be associated with differences in early stem development, although maternal, paternal and cytoplasmic effects were not separately evaluated in the present experiment. The relatively greater stem diameter observed in these progenies may indicate stronger early structural development and seedling vigour (Dadhaniya et al., 2020).

3.2.3 Leaf Length

The maximum leaf length (8.72 cm) was recorded in GJCA-1 × Mammoth (C₂₀), which was statistically at par with Mammoth × Balanagar (C₁₄) and Selection 11 × GJCA-1 (C₄), whereas the minimum leaf length (5.98 cm) was recorded in Selection 11 × Sindhan (C₂). Contrasting performance was observed among several reciprocal combinations. Mammoth × Balanagar (C₁₄) recorded greater leaf length than its reciprocal Balanagar × Mammoth (C₇) (8.59 vs. 6.04 cm), while GJCA-1 × Mammoth (C₂₀) recorded greater leaf length than its reciprocal Mammoth × GJCA-1 (C₁₆) (8.72 vs. 7.17 cm). Similarly, Sindhan × Balanagar (C₁₀) recorded greater leaf length than its reciprocal Balanagar × Sindhan (C₆) (8.03 vs. 6.46 cm). These contrasting performances suggest that cross direction may be associated with differences in leaf expansion in F₁ progenies, although maternal, paternal and cytoplasmic effects were not separately evaluated in the present experiment. Greater leaf dimensions may contribute to a larger potential photosynthetic surface, which may support early vegetative development (Jnapika et al., 2021).

3.2.4 Leaf Width

The maximum leaf width (3.32 cm) was recorded in GJCA-1 × Mammoth (C₂₀), which was statistically at par with Selection 11 × Mammoth (C₃) and Sindhan × Balanagar (C₁₀), whereas the minimum leaf width (2.32 cm) was recorded in Selection 11 × Sindhan (C₂). Contrasting performance was observed among several reciprocal combinations. Selection 11 × Sindhan (C₂) recorded lower leaf width than its reciprocal Sindhan × Selection 11 (C₉) (2.32 vs. 3.08 cm), while Selection 11 × Mammoth (C₃) recorded greater leaf width than its reciprocal Mammoth × Selection 11 (C₁₃) (3.31 vs. 2.65 cm). Similarly, Sindhan × Balanagar (C₁₀) recorded greater leaf width than its reciprocal Balanagar × Sindhan (C₆) (3.25 vs. 2.63 cm) and GJCA-1 × Mammoth (C₂₀) recorded greater leaf width than its reciprocal Mammoth × GJCA-1 (C₁₆) (3.32 vs. 2.95 cm). These contrasting performances suggest that cross direction may be associated with differences in leaf expansion in F₁ progenies, although maternal, paternal and cytoplasmic effects were not separately evaluated in the present experiment. Greater leaf dimensions may contribute to a larger potential photosynthetic surface, which may support early vegetative development (Jnapika et al., 2021).

Table 1. Comparative performance of custard apple F₁ progenies for germination and seedling growth parameters

Sl. no.	Trt. details	Days to first emergence	Germination (%)	Plant height (cm)	Stem diameter (mm)	Leaf length (cm)	Leaf width (cm)
C ₁	Selection 11 x Balanagar	26.00 ^{bcd}	57.51 ^e	22.49 ^{gh}	3.38 ^b	7.58 ^d	2.84 ^{fg}
C ₂	Selection 11 x Sindhan	25.66 ^{cd}	65.99 ^d	18.91 ⁱ	2.68 ⁱ	5.98 ^g	2.32 ^k
C ₃	Selection 11 x Mammoth	28.33 ^a	58.29 ^e	25.36 ^{de}	3.66 ^a	7.52 ^{de}	3.31 ^a
C ₄	Selection 11 x GJCA-1	26.96 ^b	71.56 ^c	30.65 ^a	3.70 ^a	8.40 ^{ab}	3.15 ^{bc}
C ₅	Balanagar x Selection 11	24.33 ^{ef}	70.03 ^c	28.18 ^b	3.25 ^{bc}	8.08 ^{bc}	2.66 ^h
C ₆	Balanagar x Sindhan	22.66 ^g	86.92 ^a	19.44 ⁱ	2.67 ⁱ	6.46 ^h	2.63 ^h
C ₇	Balanagar x Mammoth	26.00 ^{bcd}	71.87 ^c	23.97 ^f	3.08 ^{def}	6.04 ^g	2.45 ^{ij}
C ₈	Balanagar x GJCA-1	25.25 ^{de}	86.10 ^a	26.08 ^{cd}	2.98 ^{fg}	7.69 ^{cd}	2.54 ^{hij}
C ₉	Sindhan x Selection 11	22.99 ^g	65.37 ^d	22.13 ^h	3.19 ^{cd}	7.14 ^{ef}	3.08 ^{cd}
C ₁₀	Sindhan x Balanagar	25.17 ^{de}	71.66 ^c	26.80 ^c	3.37 ^b	8.03 ^{bc}	3.25 ^{ab}
C ₁₁	Sindhan x Mammoth	23.66 ^{fg}	79.78 ^b	16.40 ^j	2.77 ^{hi}	7.05 ^f	2.56 ^{hi}
C ₁₂	Sindhan x GJCA-1	24.33 ^{ef}	79.54 ^b	23.92 ^f	3.17 ^{cde}	7.84 ^{cd}	2.43 ^{jk}
C ₁₃	Mammoth x Selection 11	26.67 ^{bc}	79.64 ^b	26.22 ^{cd}	2.86 ^{gh}	7.44 ^{def}	2.65 ^h
C ₁₄	Mammoth x Balanagar	23.50 ^{fg}	65.35 ^d	30.46 ^a	3.38 ^b	8.59 ^a	3.02 ^d
C ₁₅	Mammoth x Sindhan	25.18 ^{de}	65.92 ^d	25.65 ^{cd}	3.09 ^{def}	7.09 ^f	2.44 ^{ijk}
C ₁₆	Mammoth x GJCA-1	26.09 ^{bcd}	79.42 ^b	23.58 ^{fg}	3.03 ^{ef}	7.17 ^{ef}	2.95 ^{ef}
C ₁₇	GJCA-1 x Selection 11	26.33 ^{bcd}	79.81 ^b	24.36 ^{ef}	3.20 ^{cd}	7.75 ^{cd}	2.78 ^g
C ₁₈	GJCA-1 x Balanagar	27.18 ^{ab}	71.03 ^c	28.65 ^b	2.45 ^j	7.78 ^{cd}	2.85 ^{fg}
C ₁₉	GJCA-1 x Sindhan	25.33 ^{de}	79.11 ^b	23.08 ^{fgh}	3.27 ^{bc}	7.16 ^{ef}	2.54 ^{hij}
C ₂₀	GJCA-1 x Mammoth	28.18 ^a	71.35 ^c	30.42 ^a	3.30 ^{bc}	8.72 ^a	3.32 ^a
Maximum		28.33	86.92	30.65	3.70	8.72	3.32
Minimum		22.66	57.51	16.40	2.45	5.98	2.32
Mean		25.49	72.81	24.84	3.12	7.48	2.79
S.E.m. _±		0.397	1.173	0.415	0.046	0.123	0.040
C.D. (p = 0.05)		1.14	3.36	1.20	0.33	0.35	0.12
C.V. %		2.75	2.27	2.90	2.56	2.84	2.51

Note: Means followed by the same superscript letter are not significantly different at $p = 0.05$ according to Duncan's Multiple Range Test

4. Conclusions

The comparative evaluation of 20 F₁ custard apple cross combinations demonstrated significant variation in germination behaviour and early seedling growth under the nursery conditions of the study. Days to first emergence ranged from 22.66 to 28.33 days, while

germination percentage ranged from 57.51 to 86.92%. Balanagar $\times$ Sindhan (C₆) combined the earliest emergence with the highest germination percentage. Selection 11 $\times$ GJCA-1 (C₄) recorded the greatest plant height and stem diameter, whereas GJCA-1 $\times$ Mammoth (C₂₀) produced the greatest leaf length and leaf width. Several reciprocal combinations also differed in their performance, indicating that cross direction may be associated with variation in early seedling traits; however, the present design did not separately test maternal, paternal or cytoplasmic effects. These findings support the evaluation of multiple progeny traits rather than reliance on a single early-growth character. The comparatively better-performing progenies identified here may be retained for further nursery and field evaluation to determine whether their early advantages are maintained at subsequent growth stages.

5. Limitations

The present investigation was conducted under nursery conditions during a single season and was limited to the evaluation of germination behaviour and early seedling growth of F₁ progenies up to 90 days after sowing. Therefore, the observed differences among cross combinations may not necessarily reflect their long-term growth performance under field conditions. Further multi-season and multi-location evaluation of the selected F₁ progenies is required to validate the consistency of their seedling vigour and to assess their subsequent growth and performance under field conditions.

Acknowledgements

I sincerely acknowledge the valuable guidance, constant encouragement and support provided by my guide throughout the course of this investigation. I also gratefully acknowledge the Government of Gujarat for providing financial assistance through the SHODH (Scheme of Developing High-quality Research) Fellowship, which supported the successful completion of this research work.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interest exists.

References

- Anaya-Esparza, L. M., García-Magaña, M. de L., Domínguez-Ávila, J. A., Yahia, E. M., Salazar-López, N. J., González-Aguilar, G. A., & Montalvo-González, E. (2020). Annonas: Underutilized species as a potential source of bioactive compounds. *Food Research International*, 138, 109775. <https://doi.org/10.1016/j.foodres.2020.109775>
- Bisht, M. S., Mahajan, S., Chakraborty, A., & Sharma, V. K. (2025). A high-quality genome assembly of *Annona squamosa* (custard apple) provides functional insights into an emerging fruit crop. *DNA Research*, 32(3), dsaf007. <https://doi.org/10.1093/dnares/dsaf007>
- Chagas, P. C., Chagas, E. A., Crane, J. H., Vendrame, W., Chambers, A., Costa, B. N. S., & Neto, A. R. (2022). Effect of naphthalene acetic acid, gibberellic acid, and spray adjuvant alone or in conjunction with hand pollination on fruit set and quality of 'LeahReese' sugar apple (*Annona squamosa* L.). *Scientia Horticulturae*, 299, 111011. <https://doi.org/10.1016/j.scienta.2022.111011>
- Dadhaniya, D. B., Kanzaria, D. R., Sejal, B., Dhara, T., & Varuti, P. (2020). Effect of time of sowing and chemical treatments on seedling growth of custard apple (*Annona squamosa* L.) cv. Sindhan. *Chemical Science Review and Letters*, 9(33), 19–23. <https://doi.org/10.37273/chesci.cs072050091>
- Deeksha, Sharma, T. R., & Parmar, M. (2023). The effect of different pre-sowing treatments of cow urine, soaking duration, PGPR applications and their combinations on seed germination and seedling growth parameters of custard apple (*Annona squamosa* L.). *Asian Journal of Agricultural and Horticultural Research*, 10(4), 527–537. <https://doi.org/10.9734/ajahr/2023/v10i4292>
- Gharge, V. R., Pawar, R. U., Chavan, A. K., Jadhav, Y. S., Havale, V. B., & Inamdar, P. P. (2022). Influence of GA₃ and soaking period on seed germination and seedling growth of custard apple (*Annona squamosa* L.). *Bioinfolet - A Quarterly Journal of Life Sciences*, 19(4), 426–427. <https://indianjournals.com/article/bil-19-4-024>
- Jalikop, S. H. (2010). Tree and fruit traits of progenies from the cross between (*Annona cherimola* Mill. $\times$ *A. squamosa* L.) $\times$ *A. reticulata* L. and approaches for the introgression of valuable genes from *A. reticulata* L. *Euphytica*, 173(2), 161–171. <https://doi.org/10.1007/s10681-009-0059-5>
- Jnapika, K. H., Nayan Deepak, G., Jamoh, O., Pandey, R. K., Gautam, R., & Dhakad, A. (2021). Genetic variability and correlation studies for morphological and biochemical traits of *Annona* genotypes. *The Indian Journal of Agricultural Sciences*, 91(3), 378–381. <https://doi.org/10.56093/ijas.v91i3.112468>
- Kumar, M., Changan, S., Tomar, M., Prajapati, U., Saurabh, V., Hasan, M., Sasi, M., Maheshwari, C., Singh, S., Dhumal, S., Radha, Thakur, M., Punia, S., Satankar, V., Amarowicz, R., & Mekhemar, M. (2021). Custard apple (*Annona squamosa* L.) leaves: Nutritional composition, phytochemical profile, and health-promoting biological activities. *Biomolecules*, 11(5), 614. <https://doi.org/10.3390/biom11050614>
- Leal, F., & Paull, R. E. (2023). The genus *Annona*: Botanical characteristics, horticultural requirements and uses. *Crop Science*, 63(3), 1030–1049. <https://doi.org/10.1002/csc2.20833>

- Mendes, H. T. A., Costa, M. R., Nietsche, S., Oliveira, J. A. A., & Pereira, M. C. T. (2012). Pollen grain germination and fruit set in 'Brazilian seedless' sugar apple (*Annona squamosa* L.). *Crop Breeding and Applied Biotechnology*, 12(4), 277–280. <https://doi.org/10.1590/S1984-70332012000400007>
- Mimi, C. O., Sousa, M. C., Corrêa, P. L. C., De-la-Cruz-Chacón, I., Boaro, C. S. F., & Ferreira, G. (2023). Impact of GA₃ on sugar and lipid degradation during *Annona* × *atemoya* Mabb. seed germination. *Horticulturae*, 9(3), 388. <https://doi.org/10.3390/horticulturae9030388>
- Nogueira, B. B. A. P., Mendes, D. S., Mendes, R. B., Pimenta, S., Pereira, M. C. T., Azevedo, A. M., & Nietsche, S. (2022). Selection in half-sib progenies of *Annona squamosa* L.: An important step in the development of new cultivars. *Scientia Horticulturae*, 302, 111173. <https://doi.org/10.1016/j.scienta.2022.111173>
- Okechukwu, C. L., Omosun, G., Nwaru, C. E., Onyeabor-Chinedum, N. P., & Ndukwe, N. N. (2025). Molecular, morphological and growth studies of three *Annona* species: A phylogenetic approach. *Discover Plants*, 2, 323. <https://doi.org/10.1007/s44372-025-00395-x>
- Panse, V. G., & Sukhatme, P. V. (1985). *Statistical methods for agricultural workers* (4th ed.). Indian Council of Agricultural Research.
- Prasad, S. H., Bignell, G., Copeland, R. G. R., Garg, V., Chitikineni, A., Henry, R. J., Dillon, N., Mir, R. R., & Varshney, R. K. (2025). Integrating multiomics and modern breeding tools for accelerating genetic improvement in Annonas. *Functional & Integrative Genomics*, 25, 155. <https://doi.org/10.1007/s10142-025-01653-7>
- P, P., Sharma, G. L., Chandrakar, Y. K., Sinha, Y., Yogeshwar, & Diksha. (2025). Effect of gibberellic acid (GA₃) and organic substances on seed germination and shoot growth of custard apple (*Annona squamosa* L.) seedlings under shade net condition. *Journal of Advances in Biology & Biotechnology*, 28(8), 892–898. <https://doi.org/10.9734/jabb/2025/v28i82764>
- Raghavan, M., Pradhan, V., Singh, S., Jain, S., Kumari, N., Kaur, R., Kumar, G., & Kaur, R. (2025). Advances in genetic plant breeding for horticultural crop improvement. *Plant Cell Biotechnology and Molecular Biology*, 26(7–8), 432–444. <https://doi.org/10.56557/pcbmb/2025/v26i7-89576>
- Rajpoot, S. K., Dhakar, M. K., Singh, N., Nath, V., Kumar, C., Choudhary, J. S., Bishi, S. K., Bhavana, P., Kherwar, D., Das, B., & Das, A. (2026). In-situ characterization of wild *Annona squamosa* L. genotypes reveals rich genetic diversity and elite selections for crop improvement and conservation. *Scientific Reports*, 16, 17830. <https://doi.org/10.1038/s41598-026-42155-1>
- Sahu, R. L., & Rana, G. (2024). Response of PGRs and chemical substance in seeds dormancy breaking and seedling growth of custard apple (*Annona squamosa* L.) cv. Local cultivar. *International Journal of Minor Fruits, Medicinal and Aromatic Plants*, 10(2), 24–31. <https://doi.org/10.53552/ijmfnmap.10.2.2024.24-31>
- Saunders, R. M. K. (2020). The evolution of key functional floral traits in the early divergent angiosperm family Annonaceae. *Journal of Systematics and Evolution*, 58(4), 369–392. <https://doi.org/10.1111/jse.12645>
- Singour, N., Pandey, C. S., Rai, R. K., Pandey, S. K., & Goutam, K. (2023). Effect of seed treatment and growing condition on the germination and survivality of custard apple (*Annona squamosa* L.) seedlings. *International Journal of Plant & Soil Science*, 35(21), 948–957. <https://doi.org/10.9734/ijpss/2023/v35i214065>
- Sushmitha, B. H., & Sakthivel, T. (2023). Plant genetic resources of custard apple. In P. E. Rajasekharan & V. Ramanatha Rao (Eds.), *Fruit and nut crops* (pp. 1–22). Springer Singapore. https://doi.org/10.1007/978-981-99-1586-6_17-1
- Tippannavar, A., & Singh, J. (2023). Influence of thiourea on growth parameters of jackfruit (*Artocarpus heterophyllus* L.). *Indian Journal of Arid Horticulture*, 5(1–2), 54–56. <https://doi.org/10.56093/ijah.v5i1-2.180438>

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