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RESEARCH ARTICLE

# Genetic potential of papaya genotypes: insights from agronomic descriptors and parameter estimation

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## Abstract

*Carica papaya* L., a fruit crop of high nutritional and economic importance, faces significant challenges regarding yield stability, fruit quality and environmental stress tolerance. This study explored genetic variation, heritability and trait correlations to support targeted papaya breeding programs. Through a Line × Tester mating design, 40 F1 hybrids were developed from 14 parental genotypes, revealing considerable genetic diversity. High heritability values (87.25% – 99.65%) for key traits confirmed the strong genetic influence on fruit yield, size and number of fruits per plant. Notable anticipated genetic advances, particularly for fruit yield (93.16%), emphasize the prospects for substantial improvement through selective breeding. Traits such as fruit yield per plant (45.30%), fruit weight (39.06%) and number of fruits per plant (31.46%) showed the highest genotypic and phenotypic variability. The study also highlighted the impact of environmental factors, as phenotypic coefficients of variation exceeded genotypic coefficients across traits, underlining the need for integrating ecological adaptability in breeding strategies. These results emphasize the importance of utilizing genetic diversity to enhance papaya yield and quality, meeting both domestic and global market demands. By leveraging the observed genetic potential, breeders can develop improved genotypes that align with sustainability goals, ensuring higher productivity, better market returns and enhanced food security in papaya-producing regions.

## Keywords

breeding; GCV; genetic; genotypes; heritability; PCV; yield

## Introduction

Papaya (*Carica papaya* L.) is a vital tropical fruit crop with significant global and economic importance. Originating from Central America, papaya has become a major contributor to both fresh and processed fruit markets worldwide. Globally, it holds a prominent position among fruit crops due to its high nutritional value and economic returns. Globally, the papaya market is projected to grow at a Compound Annual Growth Rate (CAGR) of 3.6%, adding nearly 2.85 million tons by 2027. The variation in papaya plants is influenced by both their genetic makeup and the environment they grow in. However, only the genetic traits can be passed on to the next generation. India's diverse papaya cultivars present opportunities to develop high-yielding varieties through hybridization. The crop's morphological diversity can be leveraged for improvement. Genetic variability and heritability are crucial for effective breeding programs, enabling the simultaneous enhancement of multiple traits.

This study aims to improve papaya yield and quality by analysing genetic variability among different traits. As papaya is a cross-fertilizing crop, it displays a wide diversity of quantitative traits that help in selecting appropriate parents for improvement programs (1).

Both their genes and the environments in which they grow contribute to the variations in papaya plants that we observe. But the only things that can be passed down to their progeny are the genetic ones (2). The crop's genetic base is quite limited (3-6). Posing a significant risk to its long-term sustainability. One viable strategy to increase the number of commercial varieties and hybrids is to expand the genetic diversity of papaya by utilizing the existing variability in germplasm banks (7-9) and developing new hybrids through breeding programs.

It is essential to focus on broadening the genetic base to produce cultivars that align with the demands of both domestic and international markets, while also being more resistant to pests, diseases, and various biotic and abiotic stresses (10, 11). India's diverse papaya cultivars offer an opportunity to develop high-yielding varieties through hybridization. Papaya shows significant morphological diversity, which can be leveraged for crop improvement. Genetic variability and heritability are crucial for effective breeding programs, enabling the simultaneous improvement of multiple traits. This study aims to enhance papaya yield and quality by analysing genetic variability among different traits. Fruit yield is a complex trait that is significantly influenced by a variety of genetic factors and environmental conditions.

On the other hand, traits related to yield components tend to have simpler inheritance patterns and are generally less affected by environmental variations (12). In plant breeding programs, directly selecting fruit yield alone may lead to misleading results (13). Line x Tester Analysis (LTA) is a statistical technique for evaluating genotype performance in various environments. LTA identifies stable and adaptable genotypes, understands genotype x environment interactions and selects superior genotypes for further breeding or commercialization. Applications of LTA include crop improvement, breeding program evaluation, genotype selection, seed production, cultivar recommendation, genetic research and precision agriculture. By applying LTA, breeders and researchers can make informed decisions, leading to improved crop performance and increased food security.

## Materials and Methods

The research study was carried out at the Sardar Vallabhbhai Patel University of Agriculture and Technology's Horticultural Research Centre in Modipuram, Meerut and this research is consistent with current climatic and weather data for the Meerut region. Subtropical climate is experienced in Meerut which is located in Uttar Pradesh, India, characterized by considerable temperature fluctuations between summer and winter seasons.

Ten papaya parent lines (Arka Prabhat, AC-119, Dwarf Lily, Red Indian, Washington, Pant papaya-2, Shantha, Line-21, CO-8, CO-2) were planted with 3 replicates in a Randomized Block Design and crossed to 4 testers (CO-7, Lucknow, Coorg Honeydew, Co-4) in Line × Tester mating system to develop 40 F1 hybrids in the year 2022-23. In the next year after developing the hybrids, along with their parents, were cultivated in a Randomized Block Design with three replications at HRC (Horticulture Research Centre), Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut.

The seeds of germplasm mention in Table 1 were obtained from ICAR-IIHR, Bangalore, sown in a nursery and later transferred to raise beds after 45-50 days of growth. NPK was applied at recommended doses for the fruit crop and additional nitrogen was sprayed at various plant stages for better Growth and improvement of the crop. Frost protection was provided by irrigation and fumigation during the winter season. The experiment yielded several key observations and measurements. During flowering, parameters such as the number of leaves at flowering, days to flowering and plant height at flowering were recorded. At harvest, observations were made on plant height, stem girth, number of fruits per plant and fruit yield per plant. Quality characteristics were also assessed and categorized into physical characteristics, including fruit weight, fruit length, pulp thickness, fruit girth and breadth of the central cavity, while chemical quality was estimated by measuring total soluble solids. The data mean values were given to a one-way ANOVA. Burton's performance was used to calculate the genotypic and phenotypic coefficients of variation (14). Heritability in the broad sense was estimated by the method of applying Lush's method and the expected genetic development for different characteristics under selection was calculated (15).

### Meteorological observations during the crop period

Meteorological data was recorded at the ICAR-Indian Institute of Farming System Research (IIFSR), located in Modipuram, Meerut, India, during the research duration. The weekly minimum and maximum temperatures for the crop season, according to meteorological data 2022, ranged from 32.3 $^0$C to 43.0 $^0$C and from 20.1 $^0$C to 43.1 $^0$C respectively. Total rainfall received was 109.3 mm, during the entire crop season, and average relative humidity of morning and evening was found to vary from 92.3% to 65.9% and the evaporation rate was maximum at 68.7 and minimum was 0.6 mm. The data was calculated as the standard meteorological week (SMW) during the experiment conducted from May 2022 to February 2023 and April 2023 to January 202

### Heritability

**Table 1.** Characterization of fourteen parent genotypes utilized in breeding programme

| Variety | Origin | Characteristics | Yield | Special features |
|---|---|---|---|---|
| **CO-7 (T)** | Tamil Nadu Agricultural University, India | Medium-sized fruits, deep orange flesh, high sweetness | High yielding | Good for fresh consumption and processing |
| **Arka Prabhat (L)** | Indian Institute of Horticultural Research (IIHR), Bangalore | Medium-sized fruits, red pulp, 1-2 kg | High yielding | Suitable for fresh consumption and processing |
| **AC-119 (L)** | Developed in India | Medium to large-sized fruits, sweet orange flesh | Good yield potential | Tolerant to some diseases |
| **Dwarf Lilly (L)** | Various sources | Small, dwarf plants, small to medium-sized fruits | Moderate yield | Suitable for small gardens and pot cultivation |
| **Red Indian (L)** | USA | Medium-sized fruits, reddish-orange flesh, sweet | Good yield | Attractive fruit color, suitable for fresh markets |
| **Washington (L)** | USA or Latin America | Large, elongated fruits, sweet yellow to orange flesh | High yielding | Popular in tropical and subtropical regions |
| **Lucknow (T)** | India | Medium-sized fruits, sweet orange flesh | Good yield potential | Known for its sweetness and flavor |
| **Coorg Honeydew (T)** | Coorg region, India | Medium to large-sized fruits, sweet deep orange flesh | High yielding | Excellent flavor and sweetness |
| **Pant-2 (L)** | Pantnagar University, India | Medium-sized fruits, deep orange flesh | Good yield potential | Good for fresh consumption and processing |
| **Shantha (L)** | Various sources | Medium-sized fruits, sweet flesh | Moderate to good yield | Suitable for fresh markets |
| **Line-21 (L)** | Developed through selection | Medium to large-sized fruits, sweet flesh | Good yield potential | Tolerant to some common diseases |
| **CO-8 (L)** | Tamil Nadu Agricultural University, India | Medium-sized fruits, deep orange flesh | High yielding | Suitable for fresh consumption and processing |
| **CO-2 (L)** | Tamil Nadu Agricultural University, India | Medium to large-sized fruits, sweet orange flesh | High yielding | Early maturing variety, suitable for fresh consumption |
| **CO-4 (T)** | Tamil Nadu Agricultural University, India | Medium-sized fruits, sweet orange flesh | Good yield potential | Suitable for fresh consumption and processing |

High heritability values indicate traits largely governed by genetic factors and are less influenced by environmental conditions. This metric aids breeders in identifying traits with potential for effective selection in breeding programs. Heritability ($h^2$) is a key parameter that quantifies the proportion of total phenotypic variance ($\sigma 2P$) attributable to genetic variance ($\sigma 2G$). It is calculated using the formula:

$$h^2 = \frac{\sigma^2 G}{\sigma^2 P} \times 100 \qquad (Eqn.1)$$

$\sigma^2G$= Genotypic Variance

$\sigma^2P$= Phenotypic Variance

### Genotypic Coefficient of Variation (GCV)

Burton's performance was used to calculate the genotypic coefficients of variation. GCV measures the extent of genetic variability relative to the mean of a trait. It provides insight into the potential of a trait for improvement through selection. The formula for GCV is:

$$GCV = \sqrt{\frac{\sigma^2 G}{Mean}} \times 100 \qquad (Eqn.2)$$

### Phenotypic Coefficient of Variation (PCV)

Burton's performance was used to calculate the phenotypic coefficients of variation. PCV evaluates the overall variability in a trait, including both genetic and environmental influences. The formula is:

$$PCV = \sqrt{\frac{\sigma^2 P}{Mean}} \times 100 \qquad (Eqn.3)$$

### Genetic Advance (% of Mean)

Genetic advance (GA) quantifies the expected improvement in a trait under selection. Expressed as a percentage of the mean, it is derived using the formula:

$$GA = K \times h^2 \times \sqrt{\sigma^2 p} \qquad (Eqn.4)$$

Here, K is the selection differential, which is usually 2.06 at 5% selection intensity. High GA values indicate traits predominantly governed by additive genetic effects and are highly responsive to selection. This metric helps breeders prioritize traits with maximum potential for genetic gain.

## Statistical Analysis

The data mean values were subjected to a one-way ANOVA (Table 2). Burton's performance was used to calculate the genotypic and phenotypic coefficients of variation. The expected genetic development for different characteristics under selection was calculated using the formula.

## Results and Discussion

### Overall Mean Performance of Parents and Hybrids

The hybrids demonstrate a significant improvement over the parents in several traits. Notably, the average fruit weight of hybrids is 1.65 kg, compared to 1.40 kg in the parents. Additionally, the hybrids exhibit a larger fruit diameter (40.43 cm) compared to the parents (39.05 cm) and greater fruit length, with hybrids averaging 20.11 cm and parents at 18.29 cm. Fruit yield per plant also sees a substantial increase in hybrids, averaging 33.88 kg, whereas the parents yield 24.66 kg. The total soluble solids (T.S.S.) content is marginally higher in hybrids (12.44) than in parents (12.37). Conversely, the parents show superior performance in certain traits. The days to flowering are fewer in parents, averaging 98.76 days, compared to 102.83 days in hybrids. Similarly, plant height at flowering is slightly greater in parents (87.70 cm) versus hybrids (88.47 cm). Plant height at harvesting also favours the parents, with an average height of 161.42 cm compared to 160.31 cm in hybrids. In some traits, the hybrids and parents exhibit comparable performance (Table 3, 4). This includes the number of leaves at flowering, stem girth, pulp thickness and breadth of the central cavity. Overall, while the hybrids show enhanced fruit traits, the parents maintain better performance in flowering time and plant height characteristics.

### Heritability

Understanding the relationship between genetic and phenotypic variance is crucial in quantitative genetics (Fig. 2), as it helps researchers to estimate the heritability of the trait. The heritability estimates for the 13 traits ranged from 87.25% to 99.65%, indicating a significant genetic contribution to the variation in these characteristics. The highest heritability values were observed for fruit weight (99.56%), fruit yield per plant (99.65%), and number of fruits per plant (98.50%), suggesting that genetic factors play a crucial role in determining these traits. Similarly, high heritability values were found for plant height at flowering (97.47%) and harvesting (97.91%), as well as fruit length (98.64%) and diameter (96.78%) (Table 5) (Fig. 1). These results indicate that selection for these traits is likely to be effective and genetic improvement programs can be successfully implemented to enhance the desired characteristics.

### Genotypic Coefficient of Variation (GCV)

The observed GCV values provide insights into the extent of genetic diversity present in the (Table 5) (Fig. 4) traits under study. The high GCV observed for fruit yield per plant (45.30%), number of fruits per plant (31.46%) and fruit weight (39.06%) indicates substantial genetic variability for these traits, which can be effectively exploited in breeding programs to improve overall productivity. High GCV values suggest that these traits are under significant genetic influence, providing opportunities for selecting high-performing genotypes through selection and hybridization strategies.

Moderate GCV values were recorded for traits such as the number of leaves at flowering (19.72%), plant height at harvesting (17.12%) and fruit length (23.14%), which also indicate the presence of considerable genetic variability. Traits with moderate GCV suggest a mix of genetic and environmental influences on trait expression. These traits can still be improved through selection, though with slightly less efficiency compared to traits with high GCV.

On the other hand, traits like days to flowering (6.53%) and stem girth (7.98%), which exhibited low GCV values, suggest limited genetic variability. Low GCV indicates a stronger environmental influence, making these traits less responsive to genetic improvement through conventional selection methods. For such traits, the incorporation of advanced breeding techniques, such as marker-assisted selection or genomic selection, may help identify and utilize underlying genetic factors effectively.

### Phenotypic Coefficient of Variation (PCV)

The phenotypic coefficient of variation (PCV) values reveals the combined influence of genetic and environmental factors on trait expression. Very high PCV values were observed for fruit yield per plant (45.38%), fruit weight (39.15%), and number of fruits per plant (31.69%), indicating a significant contribution of environmental factors in addition to genetic variability

**Table 2.** ANOVA for parent and hybrids

| Charac-ters | d.f. | Days at flower-ing | Plant height at flow-ering (cm) | Plant height at har-vesting (cm) | No. of leaves at flower-ing | Stem girth (mm) | No. of fruit per plant | Fruit weig ht (kg) | Fruit diame-ter (cm) | Fruit length (cm) | Pulp thick-ness (cm) | Bread th of cen-tral cavi-ty | T.S.S . (⁰ Brix) | Fruit yield per plant (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Replica-tion** | 2 | 1.35 | 4.56 | 16.89 | 1.04 | 0.26 | 1.41 | 0 | 1.19 | 0.14 | 0 | 0 | 0.23 | 0.84 |
| **Treat-ment** | 53 | 139.03** | 440.44** | 2283.9** | 93.70** | 15.59** | 347.53** | 1.15** | 92.31** | 62.26** | 0.43** | 2.25** | 2.99** | 611.18** |
| **Error** | 106 | 6.46 | 3.78 | 16.11 | 1.5 | 0.54 | 1.76 | 0 | 1.01 | 0.29 | 0.01 | 0.05 | 0.11 | 0.72 |
| **Total** | 161 | 50.04 | 147.54 | 762.66 | 31.84 | 5.49 | 115.58 | 0.38 | 31.07 | 20.68 | 0.15 | 0.77 | 1.06 | 201.68 |

** significant at 5% and 1% level respectively.

**Table 3.** Mean performance of the parents (2022-2024)

| Parents | Days at flowering | Plant height at flowering (cm) | Plant height at harvesting (cm) | No. of leaves at flowering | Stem girth (mm) | No. of fruit per plant | Fruit weight (kg) | Fruit diameter (cm) | Fruit length (cm) | Pulp thickness (cm) | Breadth of central cavity (cm) | T.S.S. ($^{o}$ Brix) | Fruit yield per plant (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **(LINE)** Arka Prabhat | 97 | 80.65 | 144.77 | 23 | 29.5 | 16.33 | 0.98 | 35.49 | 13.6 | 3.12 | 8.2 | 12.1 | 9.68 |
| AC-119 | 85.33 | 69.45 | 119.97 | 26 | 25.89 | 59.67 | 0.74 | 36.8 | 15.2 | 2.81 | 8.1 | 11.4 | 25.76 |
| Dwarf Lily | 83 | 71.02 | 110.17 | 19 | 22.87 | 31.33 | 0.72 | 39.11 | 14.7 | 2.91 | 7.9 | 13.2 | 15.39 |
| Red Indian | 95 | 80.45 | 134.93 | 29 | 29.6 | 32.67 | 2.2 | 40.3 | 28 | 3.7 | 7.3 | 13.1 | 37.94 |
| Washington | 110.33 | 90.76 | 210.1 | 31.67 | 29.67 | 26.33 | 0.89 | 32.13 | 13.1 | 3.29 | 6.9 | 11.4 | 15.38 |
| Pant Papaya-2 | 98.33 | 84.09 | 186.73 | 23 | 26.98 | 21.33 | 1.29 | 41.17 | 17.9 | 2.56 | 7.8 | 11.4 | 18.43 |
| Shantha | 104.67 | 98.05 | 174 | 38 | 31.2 | 31 | 1.5 | 38.2 | 24 | 3.34 | 8.7 | 13.2 | 25.39 |
| Line-21 | 88.33 | 69.78 | 112.97 | 32.33 | 25.67 | 17 | 2.6 | 43.2 | 17.9 | 3.4 | 8.5 | 12.4 | 25.77 |
| CO-8 | 103 | 86.79 | 154.07 | 33 | 33.1 | 33.33 | 1.8 | 33.83 | 26.44 | 2.96 | 8.3 | 11.4 | 33.12 |
| CO-2 | 107.67 | 103.04 | 188.93 | 28.67 | 30.3 | 44.33 | 2.56 | 55.2 | 21.2 | 3.98 | 10.1 | 13.6 | 57.47 |
| **(TESTER)** CO-7 | 102 | 98.56 | 181.07 | 19 | 30.1 | 22 | 1.1 | 38.4 | 17.3 | 3.13 | 7.6 | 11.2 | 18.57 |
| Lucknow | 99.33 | 84.45 | 155.1 | 26 | 25.78 | 17 | 0.8 | 36.79 | 12.77 | 3.01 | 6.4 | 12.6 | 8.62 |
| Coorg Honeydew | 97 | 129.12 | 218.9 | 37.67 | 27.9 | 39.67 | 1.4 | 39.63 | 17.67 | 2.68 | 7.85 | 12.8 | 28.67 |
| CO-4 | 111.67 | 81.56 | 168.2 | 24 | 26.41 | 41.67 | 1.03 | 36.42 | 16.3 | 3.04 | 7.7 | 13.4 | 24.99 |
| **Mean** | **98.76** | **87.7** | **161.42** | **27.88** | **28.21** | **30.98** | **1.4** | **39.05** | **18.29** | **3.14** | **7.95** | **12.37** | **24.66** |
| **Min** | 83 | 69.45 | 110.17 | 19 | 22.87 | 16.33 | 0.72 | 32.13 | 12.77 | 2.56 | 6.4 | 11.2 | 8.62 |
| **Max** | 111.67 | 129.12 | 218.9 | 38 | 33.1 | 59.67 | 2.6 | 55.2 | 28 | 3.98 | 10.1 | 13.6 | 57.47 |

(Table 5) (Fig. 3). These findings highlight the need for careful environmental management and multi-location trials to accurately assess the genetic potential of these traits.

Moderate PCV values were recorded for traits like the number of leaves at flowering (20.19%), plant height at harvesting (17.30%), and fruit diameter (14.00%), suggesting that these traits are influenced by both genetic and environmental factors to a moderate extent. Selection efforts for such traits should consider both environmental and genetic variances to achieve reliable improvements.

In contrast, low PCV values for traits such as stem girth (8.40%) and days to flowering (6.99%) suggest that these traits are less influenced by the environment and are relatively stable across different conditions. However, their low genotypic variability, as indicated by corresponding GCV values, implies limited potential for significant improvement through conventional selection. These results are also following previous findings (16).

**Table 4.** Mean performance of the hybrids developed by crossing (2023-2024).

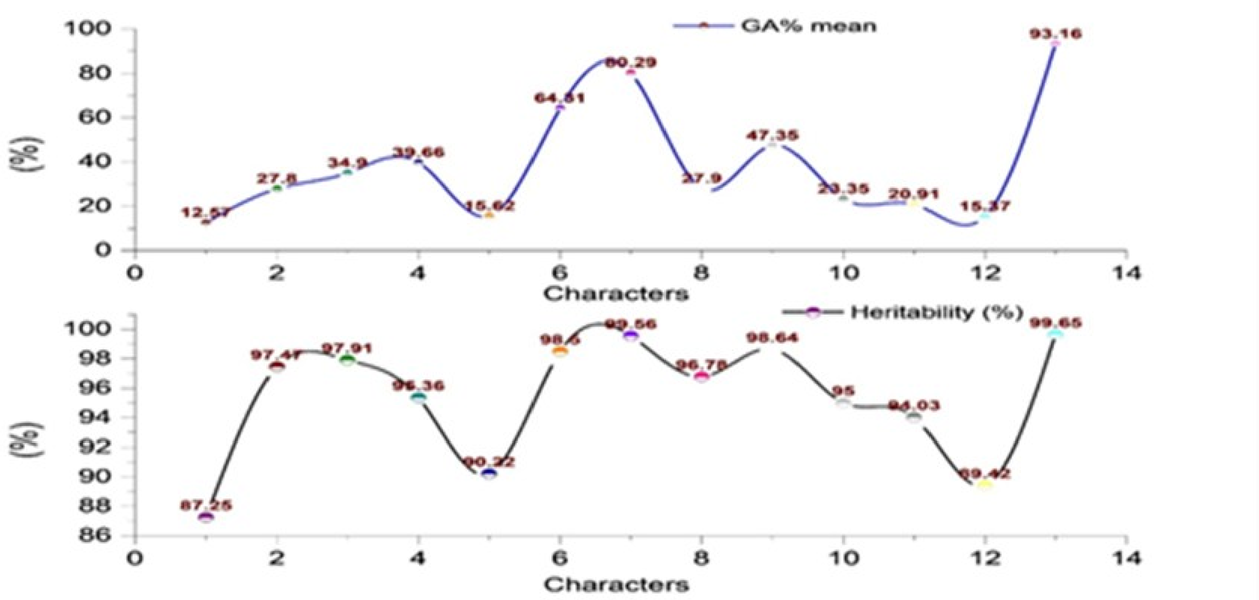


**Fig 1.** Estimates of genetic advance as percent of mean and heritability percent.

**1. Days at flowering 2. Plant height at flowering (cm) 3. Plant height at harvesting (cm) 4. No. of leaves at flowering 5. Stem girth (mm) 6. No. of fruit per plant 7. Fruit weight (kg) 8. Fruit diameter (cm) 9. Fruit length (cm) 10. Pulp thickness (cm) 11. Breadth of central cavity (cm) 12. T.S.S.13. Fruit yield per plant (kg)**

| $F_1$-Hybrids | Days at flowering | Plant height at flowering (cm) | Plant height at harvesting (cm) | No. Of leaves at flowering | Stem girth (mm) | No. Of fruit per plant | Fruit weight (kg) | Fruit diameter (cm) | Fruit length (cm) | Pulp thickness (cm) | Breadth of central cavity (cm) | T.S.S. | Fruit yield per plant (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arka Prabhat × CO-7 | 103.33 | 83.87 | 144.7 | 24 | 29.92 | 19 | 1.19 | 37.82 | 17.96 | 3.29 | 8.32 | 11.2 | 15.65 |
| Arka Prabhat × Lucknow | 93 | 80.12 | 139.67 | 25 | 25.75 | 18.33 | 0.96 | 36.39 | 13.15 | 3.12 | 8.23 | 12.43 | 15.89 |
| Arka Prabhat × Coorg Honeydew | 101 | 110.32 | 157.63 | 31.33 | 27.5 | 41.67 | 1.53 | 37.23 | 16.61 | 3.11 | 8.21 | 12.98 | 33.43 |
| Arka Prabhat × CO-4 | 107 | 79.44 | 141.8 | 27 | 26.41 | 41 | 1.1 | 35.38 | 15.37 | 3.16 | 7.98 | 11.34 | 27.09 |
| AC-119 × CO-7 | 102.33 | 79.45 | 126.97 | 22 | 27.5 | 51.67 | 0.89 | 37.59 | 17.87 | 3.19 | 8.56 | 11.1 | 28.88 |
| AC-119 × Lucknow | 94.67 | 76.89 | 143.93 | 30 | 26.5 | 52.67 | 0.78 | 36.55 | 15.44 | 2.93 | 8.49 | 13.24 | 25.78 |
| AC-119 × Coorg Honeydew | 98 | 89.45 | 139 | 21 | 27.79 | 59.67 | 1.44 | 39.61 | 18.24 | 2.91 | 8.42 | 13.89 | 48.54 |
| AC-119 × CO-4 | 96 | 73.65 | 128.81 | 27 | 26.5 | 50 | 1.11 | 36.66 | 16.21 | 3.08 | 8.12 | 11.32 | 31.77 |
| Dwarf Lily × CO-7 | 98 | 91.43 | 135.9 | 16.67 | 27.25 | 28 | 1.12 | 38.87 | 18.11 | 3.1 | 7.63 | 12.6 | 20.33 |
| Dwarf Lily × Lucknow | 97 | 74.35 | 123.8 | 22.67 | 23.69 | 32.33 | 0.76 | 37.92 | 14.52 | 2.96 | 7.98 | 12.43 | 18.56 |
| Dwarf Lily × Coorg Honeydew | 95.33 | 94.34 | 154.97 | 36.67 | 25.4 | 33 | 1.21 | 39.55 | 18.21 | 2.98 | 7.53 | 11.45 | 27.54 |
| Dwarf Lily × CO-4 | 95.67 | 76.9 | 115.93 | 28 | 22.23 | 41 | 0.82 | 39.1 | 15.97 | 3.09 | 7.97 | 12.6 | 20.98 |
| Red Indian × CO-7 | 103.33 | 90.43 | 158.77 | 35 | 29.5 | 28.67 | 2.32 | 38.87 | 27.93 | 3.89 | 7.49 | 12.49 | 36.47 |
| Red Indian × Lucknow | 98 | 78.57 | 141.97 | 25 | 27.92 | 34 | 2.23 | 38.9 | 27.75 | 3.79 | 7.12 | 12.98 | 42.34 |
| Red Indian × Coorg Honeydew | 101.67 | 112.65 | 161.63 | 31 | 28.88 | 42.33 | 2.19 | 40.24 | 29.12 | 3.76 | 7.61 | 11.67 | 50.34 |
| Red Indian × Co-4 | 112 | 78.45 | 158.63 | 22 | 26.28 | 36.33 | 2.33 | 40.21 | 27.67 | 3.85 | 7.86 | 11.43 | 48.65 |
| Washington × CO-7 | 111.67 | 98.47 | 190.8 | 32 | 30.62 | 26 | 1.17 | 34.88 | 16.35 | 3.43 | 6.89 | 12.54 | 18.66 |
| Washington × Lucknow | 110.67 | 85.37 | 163.5 | 26.67 | 31.58 | 20 | 0.8 | 37.23 | 13.1 | 3.21 | 6.5 | 13.43 | 12.54 |
| Washington × Coorg Honeydew | 108 | 97.53 | 209.63 | 40.33 | 30.5 | 39 | 1.4 | 36.89 | 18.27 | 3.22 | 6.8 | 12.99 | 28.54 |
| Washington × CO-4 | 114.67 | 88.67 | 181.77 | 27 | 29.81 | 33.67 | 1.13 | 35.42 | 15.44 | 3.36 | 7.89 | 11.67 | 24.93 |
| Pant Papaya-2 × CO-7 | 103.67 | 89.44 | 181.57 | 30 | 28.77 | 22.33 | 1.24 | 43.12 | 17.87 | 2.67 | 7.87 | 12 | 15.44 |
| Pant Papaya-2 × Lucknow | 99.67 | 83.45 | 151.53 | 28 | 28.2 | 22.33 | 1.23 | 41.59 | 17.84 | 2.1 | 7.5 | 14.56 | 16.76 |
| Pant Papaya-2 × Coorg Honeydew | 105 | 89.59 | 191.6 | 19 | 28.32 | 42 | 1.58 | 39.94 | 18.38 | 3.23 | 7.9 | 12.13 | 39.43 |
| Pant Papaya-2 × CO-4 | 108.67 | 86.45 | 180.6 | 27.33 | 28.13 | 32 | 1.24 | 43.52 | 19.23 | 2.85 | 7.88 | 12.98 | 23.12 |
| Shantha × CO-7 | 100.67 | 96.55 | 174.33 | 26 | 28.23 | 27 | 1.7 | 38.23 | 24.21 | 3.54 | 8.51 | 13 | 26.32 |
| Shantha × Lucknow | 99 | 90.68 | 156.7 | 32 | 29.72 | 31 | 1.6 | 37.93 | 24.92 | 3.32 | 8.49 | 15.92 | 28.43 |
| Shantha × Coorg Honeydew | 103.67 | 107.89 | 188.83 | 31 | 31.02 | 36.67 | 1.7 | 38.97 | 24.79 | 3.52 | 8.93 | 12.24 | 36.12 |
| Shantha × CO-4 | 106.67 | 87.24 | 143.5 | 32 | 24.92 | 41.67 | 1.7 | 37.88 | 23.67 | 3.56 | 8.79 | 11.56 | 37.88 |
| Line-21 × CO-7 | 96 | 85.34 | 141.6 | 22 | 29.22 | 20 | 2.59 | 42.5 | 18.73 | 3.58 | 8.55 | 13.1 | 28.12 |
| Line-21 × Lucknow | 96.33 | 76.22 | 138.7 | 27.67 | 26.85 | 19.33 | 2.61 | 44.22 | 18.87 | 3.47 | 8.53 | 12.54 | 30.54 |
| Line-21 × Coorg Honeydew | 96.33 | 82.88 | 146.77 | 35.33 | 24.68 | 43.67 | 2.31 | 44.29 | 18.68 | 3.49 | 8.48 | 11.41 | 62.12 |
| Line-21 × CO-4 | 97.67 | 72.54 | 148.53 | 29 | 26.23 | 27.33 | 2.59 | 44.52 | 18.56 | 3.62 | 8.56 | 12.31 | 41.32 |
| CO-8 × CO-7 | 108 | 88 | 181 | 25.33 | 27.92 | 35 | 1.94 | 39.61 | 22.66 | 3.1 | 8.67 | 12.3 | 37.09 |
| CO-8 × Lucknow | 103.67 | 78.41 | 134.67 | 35 | 30.52 | 33.33 | 1.92 | 34.89 | 26.79 | 2.94 | 8.37 | 13.22 | 36.66 |
| CO-8 × Coorg Honeydew | 105 | 91.11 | 164.8 | 34.33 | 31.24 | 37 | 1.59 | 36.23 | 26.82 | 2.96 | 8.32 | 11.22 | 34.43 |
| CO-8 × CO-4 | 109.67 | 84.79 | 161.83 | 31 | 30.23 | 37 | 1.97 | 34.23 | 24.61 | 3.27 | 8.62 | 11.11 | 39.44 |
| CO-2 × CO-7 | 106.67 | 92.56 | 188.97 | 20 | 27.65 | 43.67 | 2.53 | 55.22 | 19.75 | 3.87 | 10.41 | 12.5 | 60.65 |
| CO-2 × Lucknow | 106 | 96.9 | 195.77 | 34.67 | 27.59 | 43.67 | 2.53 | 53.78 | 22.22 | 3.82 | 10.14 | 11.45 | 61.32 |
| CO-2 × Coorg Honeydew | 108.33 | 114.33 | 223.6 | 36 | 29.85 | 43.33 | 2.62 | 55.87 | 21.94 | 3.82 | 10.16 | 14.43 | 63.12 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CO-2 × CO-4 | 111.33 | 104.22 | 197.77 | 22 | 29.32 | 42.67 | 2.18 | 55.19 | 20.58 | 3.03 | 10.15 | 11.65 | 60.02 |
| **Mean** | **102.83** | **88.47** | **160.31** | **28.2** | **28** | **35.23** | **1.65** | **40.43** | **20.11** | **3.28** | **8.26** | **12.44** | **33.88** |
| **Min** | 93 | 72.54 | 115.93 | 16.67 | 22.23 | 18.33 | 0.76 | 34.23 | 13.1 | 2.1 | 6.5 | 11.1 | 12.54 |
| **Max** | 114.67 | 114.33 | 223.6 | 40.33 | 31.58 | 59.67 | 2.62 | 55.87 | 29.12 | 3.89 | 10.41 | 15.92 | 63.12 |
| **Mean** | **101.78** | **88.27** | **160.6** | **28.12** | **28.06** | **34.13** | **1.58** | **40.07** | **19.64** | **3.24** | **8.18** | **12.42** | **31.49** |
| **Min** | 83 | 69.45 | 110.17 | 16.67 | 22.23 | 16.33 | 0.72 | 32.13 | 12.77 | 2.1 | 6.4 | 11.1 | 8.62 |
| **Max** | 114.67 | 129.12 | 223.6 | 40.33 | 33.1 | 59.67 | 2.62 | 55.87 | 29.12 | 3.98 | 10.41 | 15.92 | 63.12 |
| **SE(d)** | 2.08 | 1.59 | 3.28 | 1 | 0.6 | 1.08 | 0.03 | 0.82 | 0.44 | 0.07 | 0.18 | 0.28 | 0.69 |
| **C.D.** | 4.12 | 3.15 | 6.51 | 1.98 | 1.2 | 2.15 | 0.07 | 1.63 | 0.87 | 0.14 | 0.35 | 0.55 | 1.38 |
| **CV** | 2.5 | 2.2 | 2.5 | 4.35 | 2.63 | 3.89 | 2.61 | 2.51 | 2.72 | 2.67 | 2.64 | 2.71 | 2.69 |

**Table 5.** Genetic variability among different traits

| Character | Mean | Min. | Max | Variance (g) | Variance (p) | Heritability (%) | GA | GA% mean | GCV (%) | PCV (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Days at flowering** | 101.78 | 83 | 114.67 | 44.19 | 50.65 | 87.25 | 12.79 | 12.57 | 6.53 | 6.99 |
| **Plant height at flowering (cm)** | 88.27 | 69.45 | 129.12 | 145.55 | 149.34 | 97.47 | 24.54 | 27.8 | 13.67 | 13.84 |
| **Plant height at harvesting (cm)** | 160.6 | 110.17 | 223.6 | 755.93 | 772.04 | 97.91 | 56.04 | 34.9 | 17.12 | 17.3 |
| **No. of leaves at flowering** | 28.12 | 16.67 | 40.33 | 30.73 | 32.23 | 95.36 | 11.15 | 39.66 | 19.72 | 20.19 |
| **Stem girth (mm)** | 28.06 | 22.23 | 33.1 | 5.02 | 5.56 | 90.22 | 4.38 | 15.62 | 7.98 | 8.4 |
| **No. of fruit per plant** | 34.13 | 16.33 | 59.67 | 115.26 | 117.02 | 98.5 | 21.95 | 64.31 | 31.46 | 31.69 |
| **Fruit weight (kg)** | 1.58 | 0.72 | 2.62 | 0.38 | 0.38 | 99.56 | 1.27 | 80.29 | 39.06 | 39.15 |
| **Fruit diameter (cm)** | 40.07 | 32.13 | 55.87 | 30.43 | 31.45 | 96.78 | 11.18 | 27.9 | 13.77 | 14 |
| **Fruit length (cm)** | 19.64 | 12.77 | 29.12 | 20.66 | 20.94 | 98.64 | 9.3 | 47.35 | 23.14 | 23.3 |
| **Pulp thickness (cm)** | 3.24 | 2.1 | 3.98 | 0.14 | 0.15 | 95 | 0.76 | 23.35 | 11.63 | 11.93 |
| **Breadth of central cavity (cm)** | 8.18 | 6.4 | 10.41 | 0.73 | 0.78 | 94.03 | 1.71 | 20.91 | 10.47 | 10.79 |
| **T.S.S.** | 12.42 | 11.1 | 15.92 | 0.96 | 1.07 | 89.42 | 1.91 | 15.37 | 7.89 | 8.34 |
| **Fruit yield per plant (kg)** | 31.49 | 8.62 | 63.12 | 203.49 | 204.2 | 99.65 | 29.33 | 93.16 | 45.3 | 45.38 |

**Table 6.** Promising line and tester genotypes based on their performance

| Trait | Promising lines | Promising testers | Key observations |
|---|---|---|---|
| **Days to flowering** | AC-119, Dwarf Lily, Line-21 | Lucknow | Early flowering was promoted by AC-119; delayed flowering was observed in Washington and Co-2. |
| **Plant height** | Shantha, Co-2 | Coorg Honeydew | Increased height linked to Shantha and Co-2; shorter plants promoted by AC-119. |
| **Number of leaves** | Washington, Shantha, Co-8 | Coorg Honeydew | Positive GCA effects for higher leaf count; reduced leaves in Arka Prabhat. |
| **Stem girth** | Washington, Co-8 | Coorg Honeydew, Co-7 | Thicker stems were observed in Washington and Co-8; thinner stems in Arka Prabhat. |
| **Number of fruits per plant** | AC-119, Co-2 | Coorg Honeydew | More fruits were promoted by AC-119 and Co-2; reduced fruits in Washington and Line-21. |
| **Fruit weight** | Red Indian, Co-8, Line-21 | Coorg Honeydew | Heavier fruits in Red Indian and Line-21; lighter fruits in AC-119 and Dwarf Lily. |
| **Fruit diameter** | Line-21, Co-2 | Coorg Honeydew | Larger fruit diameter linked to Line-21; smaller fruits in Arka Prabhat. |
| **Pulp thickness** | Red Indian, Shantha, Line-21 | Co-7 | Thicker pulp was observed in Shantha; thinner pulp in Arka Prabhat and AC-119. |
| **TSS (sweetness)** | Washington, Shantha, Co-8 | Lucknow | Higher TSS content promoted by Washington; reduced TSS in Arka Prabhat. |
| **Fruit yield per plant** | Red Indian, Co-2, Line-21 | Coorg Honeydew | Increased yield in Red Indian and Co-2; reduced yield in Dwarf Lily and Co-7. |

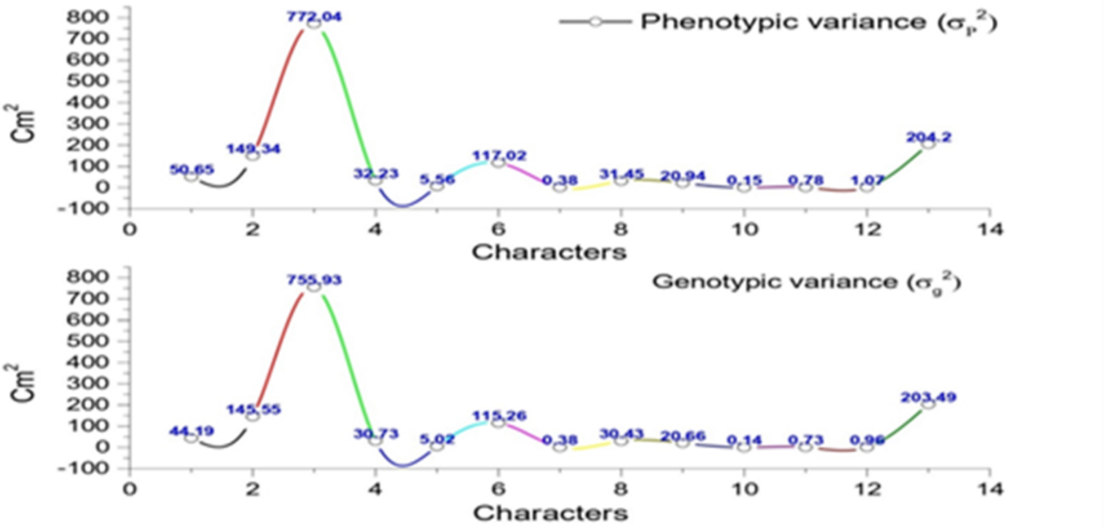


**Fig 2.** Estimates of phenotypic variance and genotypic variance.

**1. Days at flowering 2. Plant height at flowering (cm) 3. Plant height at harvesting (cm) 4. No. of leaves at flowering 5. Stem girth (mm) 6. No. of fruit per plant 7. Fruit weight (kg) 8. Fruit diameter (cm) 9. Fruit length (cm) 10. Pulp thickness (cm) 11. Breadth of central cavity (cm) 12. T.S.S.13. Fruit yield per plant (kg)**

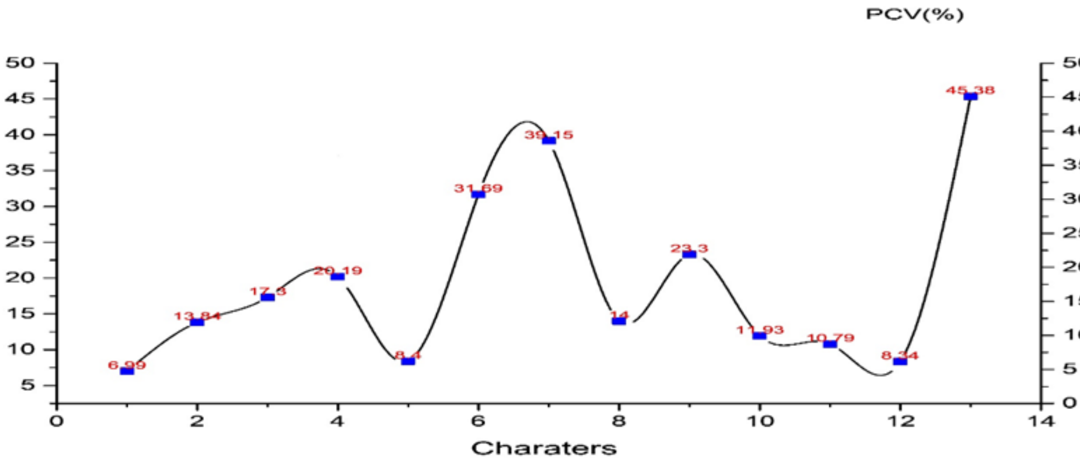


**Fig. 3.** Estimates of the phenotypic coefficient of variation.

**1. Days at flowering 2. Plant height at flowering (cm) 3. Plant height at harvesting (cm) 4. No. of leaves at flowering 5. Stem girth (mm) 6. No. of fruit per plant 7. Fruit weight (kg) 8. Fruit diameter (cm) 9. Fruit length (cm) 10. Pulp thickness (cm) 11. Breadth of central cavity (cm) 12. T.S.S.13. Fruit yield per plant (kg)**

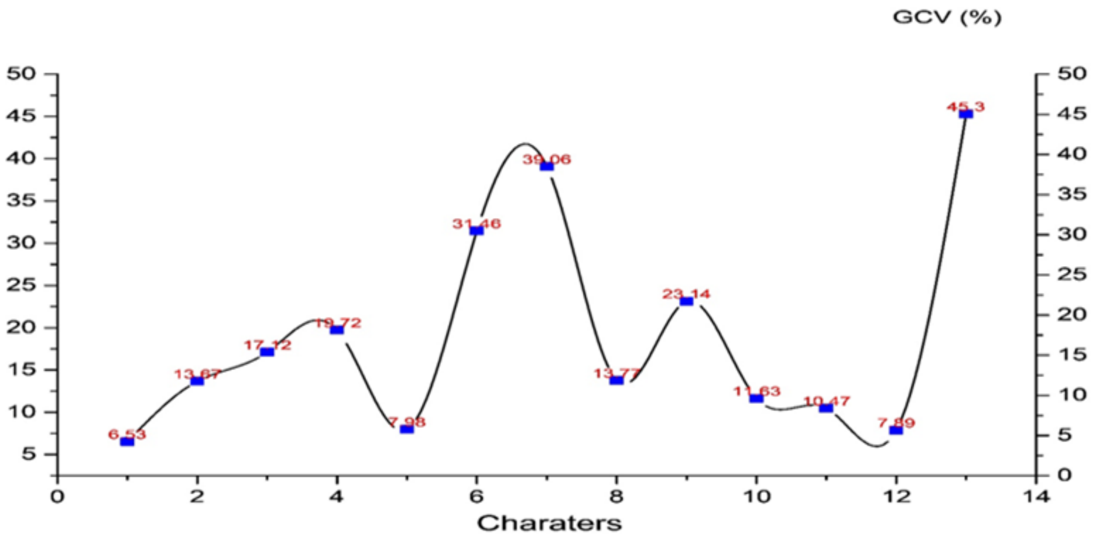


**Fig. 4.** Estimates of genotypic coefficient of variation.

**1. Days at flowering 2. Plant height at flowering (cm) 3. Plant height at harvesting (cm) 4. No. of leaves at flowering 5. Stem girth (mm) 6. No. of fruit per plant 7. Fruit weight (kg) 8. Fruit diameter (cm) 9. Fruit length (cm) 10. Pulp thickness (cm) 11. Breadth of central cavity (cm) 12. T.S.S.13. Fruit yield per plant (kg)**

### Genetic Advance (as% of mean)

The genetic advance (GA) as a percentage of the mean provides a measure of the expected improvement in a trait under selection, highlighting its potential for genetic gain. High genetic advance values were observed for fruit yield per plant (93.16%), fruit weight (80.29%) and number of fruits per plant (64.31%), indicating that these traits are governed by additive genetic effects and are highly responsive to selection (Table 5) (Fig. 1). The substantial genetic gain expected for these economically important traits suggests that they can be effectively improved through breeding programs.

Moderate genetic advance values, ranging between 20% and 30%, were recorded for traits such as breadth of the central cavity (20.91%) and pulp thickness (23.35%), suggesting a moderate scope for genetic improvement. While these traits exhibit sufficient genetic variability, their response to selection might be influenced by both genetic and environmental factors. These traits can still contribute to overall crop improvement, particularly when combined with high-yielding genotypes.

Traits with low genetic advance, such as Total Soluble Solids (15.37%) and days to flowering (12.57%), exhibited limited potential for improvement through direct selection. These low values may result from a higher influence of non-additive gene action or environmental factors, requiring alternative approaches such as hybridization or marker-assisted selection to enhance these traits.

## Conclusion

The study establishes significant potential for genetic improvement in papaya through selective breeding, emphasizing the variations observed in traits like fruit yield per plant, fruit weight and the number of fruits per plant. High Genotypic Coefficients of Variation (GCV) highlight substantial genetic diversity, while consistently higher Phenotypic Coefficients of Variation (PCV) underline the impact of environmental factors, reinforcing the need to combine genetic and phenotypic data in breeding programs.

Key findings reveal high heritability (87.25–99.65%) and moderate to high genetic advance (15.37–93.16%), underscoring the efficacy of selection for most traits. The traits identified for targeted improvement include fruit yield per plant, fruit weight and the number of fruits per plant due to their optimal combination of high heritability and genetic advance.

Based on the performance of parent genotype suggested that AC-119 is best for early flowering and Co-2 and Shantha for taller plants. Washington, Shantha and Co-8 enhanced leaf count, while Washington and Co-8 improved stem girth. AC-119 and Co-2 increased fruit count and Red Indian and Line-21 produced heavier fruits with larger diameters. Shantha improved pulp thickness and Washington enhanced TSS. Red Indian and Co-2 were superior for fruit yield, making these lines and testers ideal for breeding high-yielding, quality papaya varieties (Table 6). These insights can guide breeding programs to focus on developing sustainable, high yielding and quality papaya varieties for both fresh consumption and processing, particularly in subtropical regions. By incorporating genetic variability and environmental factors, breeders can enhance crop performance to meet the demands of industrial markets, contributing to global food security and agricultural sustainability.

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## Authors' contributions

MK and SP drafted the manuscript. BS and AK participated in the sequence alignment. LK and V participated in the design of the study and performed the statistical analysis. V, UM and RS conceived of the study and participated in its design and coordination. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Quill Bot and chat GPT in order to grammar check and language modulation. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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