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Genotypic and Phenotypic Variability and Heritability of Generative Traits, Yield Components, and The Yield in 39 Cayenne Pepper (*Capsicum annuum L.*) Genotypes

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ABSTRACT

Cayenne pepper is a horticultural crop with high economic value, and its productivity can be improved through plant breeding programs. Genotypic and phenotypic variability, and heritability are important parameters for such programs. This study aimed of obtaining information on genotypic and phenotypic variability as well as heritability of generative traits, yield components, and the yield in 39 cayenne pepper genotypes. The research was conducted from May to October 2024 at the Experimental Farm, the University of Bengkulu. A Randomized Complete Block Design (RCBD) was used, involving 39 genotypes planted in three replications, with 20 plants per replication. The results showed broad genotypic variability was found in days to anthesis, days to first harvest, number of fruits per plant, fruit diameter, fruit length, pedicel length, and average fruit weight. Broad phenotypic variability was observed in all traits. High heritability was found in days to anthesis, fruit diameter, fruit length, and average fruit weight. These findings are highly valuable for determining effective selection strategies in plant breeding and the development of superior cultivars.

INTRODUCTION

Cayenne pepper is a horticultural crop with high economic value. It has long been an essential ingredient in various cuisines, contributing a distinctive spicy flavor. Beyond its culinary applications, cayenne pepper is also widely used in traditional medicine to treat bloating and, in topical forms, to relieve back pain, headaches, and rheumatism (Djarwaningsih, 2005). Indonesia is among the countries with the highest cayenne pepper consumption globally (Kolibu et al., 2024). According to the National Food Agency, fresh consumption per capita reached 2.42 kg.year^{-1} in 2023, marking a 4.3% increase from 2022, and the highest level in the past five years (Badan Pangan Nasional, 2024). This increase aligns with population growth and the expansion of food industries that utilize cayenne pepper as a raw

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material (Pusat Data dan Sistem Informasi Pertanian, 2023).

Despite increasing demand, cayenne pepper production in Indonesia continues to face serious challenges due to the imbalance between supply and demand, leading to price volatility (Palar et al., 2016). Production enhancement may be achieved through the use of high-yielding cultivars or by expanding cultivation areas. However, due to limited access to fertile land, plant breeding, particularly the development of varieties tolerant to suboptimal conditions, emerges as a strategic solution (Limbongan, 2023).

Plant variability can be categorized into genotypic and phenotypic variability. Genotypic variability plays a fundamental role in the identification and selection of superior cultivars. A broader range of variability increases the probability of discovering individuals with desirable agronomic traits. The success of breeding programs for cayenne pepper largely depends on the effectiveness of selection methods, which must be supported by a sound understanding of trait inheritance and the identification of promising genotypes (Arif et al., 2011). Moreover, genotypic diversity enables the classification of individuals based on specific traits within a population, forming the basis for selection strategies aimed at improving yield potential and stress tolerance (Agustina and Waluyo, 2017).

In addition, phenotypic variability is also a key parameter in plant breeding, particularly through analyses based on morphological traits (Nadhifah et al., 2016). Phenotypic variability provides insight into the interaction between genotype and environment, and serves as a basis for estimating whether genetic variation is broad or narrow (Pratama et al., 2015). A high degree of phenotypic variation indicates strong potential for selecting superior genotypes, as the observed traits are sufficiently diverse and heritable.

Heritability measures the extent to which a trait can be inherited within a population (Meena et al., 2016). Its estimation helps determine the effectiveness of selection, indicating whether a trait is more influenced by genetic or environmental factors (Rosmaina et al., 2016). Selection becomes more effective when high heritability is accompanied by substantial genetic gain (Anugrah et al., 2018). Therefore, understanding heritability is crucial in determining the best selection methods to develop high-yielding superior cayenne cultivars.

This study aims to assess the genotypic and phenotypic variability, as well as the heritability, of generative traits, yield components, and the yield in a population comprising thirty-nine cayenne pepper genotypes. The resulting information will serve as a basis for selection in plant breeding programs.

MATERIALS AND METHODS

The study was conducted from May to October 2024 at the Experimental Farm, Faculty of Agriculture, University of Bengkulu, Beringin Raya Village, Bengkulu City, at an altitude of 10 meters above sea level. The soil at the site was characterized by moderate levels of nitrogen, carbon, and phosphorus; low potassium; high exchangeable aluminum (Al-dd); moderate cation exchange capacity (CEC); and very acidic pH (Table 1). No liming was applied, allowing the tested plants to express their characteristics under suboptimal soil conditions.

Weather data during the study, monthly rainfall was 300.5 mm in May, 249.1 mm in June, 205.1 mm in July, 13 mm in August, 100 mm in September, and 108 mm in October. The lowest average temperatures were recorded in August and September (27.7 °C), while the highest occurred in May and June, ranging from 29.6 to 30.1 °C. Daily sunshine duration

Table 1. Soil analysis conducted at the Soil Science Laboratory, University of Bengkulu

Parameter	Value	Category*
Nitrogen (%)	0.37	Moderate
Carbon (%)	2.11	Moderate
Phosphorus (ppm)	4.31	Moderate
Potassium (me.100 g^{-1})	0.31	Low
Exchangeable Aluminum (Al^{3+}) (me.100g^{-1})	2.61	High
Cation Exchange Capacity (CEC) (me.100g^{-1})	18.68	Moderate
pH	4.13	Highly acidic

*Categories according to Fathurrohman et al., (2023).

was 5.9 hours in May, 6.1 hours in June, 7.2 hours in July, 7.1 hours in August, 6.2 hours in September, and 6.9 hours in October. All weather parameter was considered suitable for cayenne pepper, except the rainfall which was too low. Accordingly, drip irrigation was applied consistently throughout the study to ensure adequate water supply for the plants

The experiment was arranged in a Randomized Complete Block Design (RCBD) consisting of 39 genotypes as treatments, each replicated three times. Plants were grown in plots of 1 m×4 m with a planting distance of 40 cm× 50 cm. Each plot contained 20 plants, with 5 samples. The genetic materials consisted of: ‘Mada’, ‘Baja F1’, ‘Lontanbar’, ‘Locker’, ‘Kopay’, ‘Radha’, ‘Ateng’, ‘Paten’, ‘Dumay’, ‘Lokal Legum’, ‘CMK Lolay’, ‘Indrapura Reborn’, ‘Vitra Unggul’, ‘Or Twist 42’, ‘Seulawah Aceh’, ‘Klope Lokal Aceh’, ‘Awe Aceh’, ‘CMK Tavi’, ‘Simpatik 17’, ‘Hellboy’, ‘Sempurna’, ‘Horison’, ‘Anies IPB’, ‘Iggo’, ‘Andalas’, ‘Kawat’, ‘Glora’, ‘Ferosa’, ‘Bali 77’, ‘Lajang’, ‘Tenggo’, ‘Laris’, ‘Perintis’, ‘Landung’, ‘Labek’, ‘Caman’, ‘Romario’, ‘Aka’, and ‘Vitra Op’.

The research began with soil analysis to determine levels of nitrogen (N), phosphorus (P), potassium (K), carbon (C), exchangeable aluminum ($Al3+$), cation exchange capacity (CEC), and soil pH, followed by land preparation. Seedlings were raised in a greenhouse using a 1:1 (v:v) mixture of cattle manure and topsoil. Transplanting to the field was carried out when seedlings reached four weeks after sowing. Plants were irrigated twice daily, using a drip irrigation system. Basal fertilizers applied included 400 $kg.Ha^{-1}$ of urea, 400 $kg.Ha^{-1}$ of triple superphosphate (TSP), 150 $kg.Ha^{-1}$ of potassium chloride (KCl), and 20 $tons.Ha^{-1}$ of cattle manure. Half of the urea along with all the TSP and KCl were applied at planting, while the remaining urea was top-dressed at six weeks after transplanting (WAT) (Herison et al., 2021). Supplemental fertilizers, such as NPK 16-16-16, NPK 15-09-20, calcium-boron fertilizer, monopotassium phosphate, mono-ammonium phosphate, humic substances, plant growth regulators combined with micronutrients, complete foliar fertilizer, nitrogen-rich foliar fertilizer, and ecoenzym, were applied alternately every other week via soil drenching and foliar spraying.

Pest and disease management was carried out preventively by applying Furadan 3G (a carbofuran-based granular insecticide) around the planting holes at the time of transplanting. In addition, routine weekly spraying was conducted using a combination of one type of insecticide, one fungicide, and a surfactant, at concentrations of 1–2 $ml.L^{-1}$ or 1–2 $g.L^{-1}$ of water. The insecticides used contained active ingredients such as fipronil, deltamethrin, profenofos, and diafenthiuron, while the fungicides included propineb, azoxystrobin + difenoconazole, and mancozeb. For mite control, an acaricide containing pyridaben was applied. The surfactant used contained 2-ethylhexyl sulfosuccinate as the active ingredient.

Gap filling was conducted one week after transplanting to replace dead or damaged plants. Pruning was carried out periodically by removing lateral shoots below the dichotomous branches to strengthen the main stem. Staking was performed at 21 days after transplanting using 100 cm tall bamboo stakes, with six stakes per bed connected by plastic bell ropes, and the plants were tied to the rope to prevent lodging. Harvesting was carried out every five days for fruits that had reached at least 50% red coloration. The harvest was discontinued when the plants stopped flowering and fruiting.

The observed variables included days to anthesis, days to first harvest, number of fruits per plant, fruit diameter, fruit length, pedicel length, fruit weight per plant, average fruit weight, and fruit weight per plot. The fruit weight per plot was converted to yield estimated per hectare using the following formula (Rofidah et al., 2018):

The observational data were statistically

$$\text{Yield (ton.Ha}^{-1}\text{)} = \left(\frac{10\,000\ m^2 \times 0.8}{\text{Plot area}(m^2)}\right) x \left(\frac{\text{Fruit weight per plot(g)}}{1\,000\,000\ g}\right) \quad ...(1)$$

Note: 0.8 = effective cultivated area within 1 Ha

analyzed using analysis of variance (ANOVA) with an F-test at the 5% significance level (Table 2). Genotypic and phenotypic variability were estimated using variance

Table 2. Analysis of variance calculation

Source of Variation (SV)	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	Expected Mean Square (EMS)
Replication(r)	(r-1)	SSr	MSr	-
Genotype(g)	(g-1)	SSg	MSg	$\sigma_e^2 + r\sigma_g^2$
Error(e)	(g-1) (g-1)	SSe	MSe	σ_e^2
Total(t)	gr - 1	SSt	-	

Environmental variance $(\sigma_e^2) = MSe$ ....(2)

Genotypic variance $(\sigma_g^2) = (MSg - MSe)/r$.(3)

Phenotypic variance $(\sigma_p^2) = \sigma_e^2 + \sigma_g^2$ ....(4)

component analysis. The genotypic variance and phenotypic variance were calculated using the following formulas:

The criteria for determining the extent of genotypic and phenotypic variability of the observed traits can be assessed by comparing the genotypic and phenotypic variances with their standard deviations. Genotypic variability is considered broad if the genotypic variance is equal to or greater than twice the standard deviation of the genotypic variance. Phenotypic variability is considered broad if the phenotypic variance is equal to or greater than twice its standard deviation. The standard deviation of the genotypic and phenotypic variance is estimated using the following formula (Anderson and Bancroft, 1952):

Broad-sense heritability (h^2_{bs}) was estimated

$$Sd\sigma_g^2 = \sqrt{\frac{2}{r^2}\left[\frac{(MS_g)^2}{df_g+2}\right] + \left[\frac{(MS_e)^2}{df_e+2}\right]} \quad ....(5)$$

$$Sd\sigma_p^2 = \sqrt{\frac{2}{r^2}\left[\frac{(MS_g)^2}{df_g+2}\right]} \quad ....(6)$$

Remarks:

MS_g = mean square of genotype
MS_e = mean square of error
df_g = degrees of freedom for genotype
df_e = degrees of freedom for error
r = number of replications

using variance component analysis and calculated using the following formula:

Heritability $(h^2_{bs}) = [(\sigma_g^2)/(\sigma_p^2)] \times 100\%$... (7)

Heritability is classified into three categories: 0.0–30% (Low), 31–60% (Moderate), and above 60% (High) (Comstock et al., (1949).

RESULTS AND DISCUSSION

Results

During the study, the majority of plants exhibited good growth and development, 87.11% of the population showing normal growth. The incidence of yellow virus infection was 7.93%, stunted plants accounted for 1.47%, and plant mortality was only 3.49%. These results were supported by consistent management practices, including regular irrigation, fertilization, and intensive pest and disease control. The major pests and diseases observed were fruit borer caterpillars, fruit flies, and yellow virus. Fruit borer caterpillars were identified by the presence of holes on the fruit wall, while fruit flies laid their eggs inside the fruit, which subsequently hatched into larvae that fed on the fruit flesh. Plants infected by the yellow virus exhibited symptoms such as yellowing, curling, or mosaic-patterned leaves. These pests and diseases can significantly reduce the yield potential of cayenne pepper plants.

The observed traits showed that the widest range of variation was found in the number of fruits per plant, ranging from 35 to 158, which also exhibited the highest standard deviation. The other trait ranges included yield per plot (1,548 to 4,042 g), fruit weight per plant (112 to 332 g), days to anthesis (41 to 52 days), fruit length (9.00 to 18.0 cm), days to first harvest (77 to 85 days), fruit diameter (5.00 to 13.0 mm), average fruit weight (1.6 to 6.2 g), and pedicel length (4.00 to 5.00 cm) (data are not presented).

The highest estimated yield based on fruit weight per plot was recorded in the genotype 'Baja F1', with a potential yield of 8.08 tons Ha⁻¹. This was followed by genotypes 'Caman', 'Landung', 'Aka', 'Bali 77', 'Lajang', 'Laris', 'Iggo', 'Andalas', and

'Klope Lokal Aceh', which yielded between 7.06 and 7.70 tons Ha^{-1}. Genotypes such as 'Vitra Unggul', 'Vitra OP', 'Or Twist 42', and 'Seulawah Aceh' showed yield ranging from 6.05 to 6.97 tons Ha^{-1}. A yield range of 5.09 to 5.99 tons Ha^{-1} was observed in genotypes 'Romario', 'Labek', 'Dumay', 'CMK Lolay', 'Glora', 'Indrapura Reborn', 'Paten', 'Horison', 'Kawat', 'Hellboy', 'Awe Aceh', 'Kopay', 'Lokal Legum', 'Ferosa', 'Perintis', and 'CMK Tavi'. Lower yields, between 4.04 and 4.82 tons Ha^{-1}, were found in genotypes 'Mada', 'Sempurna', 'Anies IPB', 'Radha', 'Tenggo', 'Ateng', and 'Lontanbar'. The lowest estimated yields were observed in genotypes 'Locker' and 'Simpatik 17', with values of 3.10 and 3.13 tons Ha^{-1}, respectively. The average estimated yield across the 39 cayenne pepper genotypes was 5.8 tons Ha^{-1} (data are not presented).

Variability

The level of variability among the 39 cayenne pepper genotypes ranged from narrow to broad based on the criterion of twice the standard deviation of the variance (Table 3). Most of the generative traits in the population exhibited broad genotypic variability, including days to anthesis, days to first harvest, number of fruits per plant, fruit diameter, fruit length, pedicel length, and average fruit weight. In contrast, traits such as fruit weight per plant and fruit weight per plot showed narrow variability.

Phenotypic variability indicated that the observed population possessed broad phenotypic variability (Table 3). Traits that exhibited broad phenotypic variability included all observed characteristics, such as days to anthesis, days to first harvest, number of fruits per plant, fruit diameter, fruit length, pedicel length, fruit weight per plant, average fruit weight, and fruit weight per plot.

Heritability

The heritability analysis revealed that several traits exhibited low, moderate, and high heritability estimates (Table 3). Traits such as days to anthesis, fruit diameter, fruit length, and average fruit weight showed high heritability values. Traits with moderate heritability included days to first harvest, number of fruits per plant, and pedicel length. Traits such as fruit weight per plant and fruit weight per plot showed low heritability values.

Discussion

Genotypic and phenotypic variability are fundamental parameters in the development and improvement of plant genotypes (Qosim et al., 2013). According to Effendy et al., (2018), the broader the variability of a trait within a population, the more diverse its expression, indicating a high degree of genetic control. This in turn provides greater potential to obtain superior genotypes with improved traits through selection.

In the evaluated population, nearly all traits exhibited broad genotypic variability, while all traits showed broad phenotypic variability. This suggests that the population presents considerable opportunities for breeders to select superior genotypes. However, traits such as fruit weight per plant and fruit weight

Table 3. Genotypic and phenotypic variance, and heritability estimate on generative characteristics, yield components, and yield of 39 cayenne pepper genotypes

Traits	σ_e^2	σ_g^2	$2.\mathrm{Sd}\sigma_g^2$	Criteria	σ_p^2	$2.\mathrm{Sd}\sigma_p^2$	Criteria	h^2bs (%)	Criteria
Days to anthesis	2.37	7.14	3.588	Broad	9.51	3.548	Broad	75.12	High
Days to first harvest	2.25	2.44	1.517	Broad	4.70	1.428	Broad	52.01	Moderate
Number of fruits	500.6	600.6	361.5	Broad	1101	343.2	Broad	54.54	Moderate
Fruit diameter	0.41	3.69	1.712	Broad	4.10	1.710	Broad	90.00	High
Fruit length	1.43	3.35	1.743	Broad	4.78	1.712	Broad	70.17	High
Pedicel length	0.21	0.09	0.087	Broad	0.30	0.073	Broad	31.31	Moderate
Fruit weight per plant#	7.11	0.33	2.001	Narrow	7.40	1.202	Broad	3.92	Low
Average fruit weight	0.37	1.21	0.604	Broad	1.58	0.598	Broad	76.65	High
Fruit weight per plot#	80.49	12.19	24.779	Narrow	90.97	17.195	Broad	11.53	Low

per plot exhibited narrow genotypic variability, indicating that their variation is predominantly influenced by environmental factors rather than genetic control. Lata and Sharma (2022) also stated that when genotypic variability is lower than phenotypic variability, it reflects a stronger environmental influence on trait expression compared to genetic effects.

These findings are in line with the studies by Markam and Sharma (2022), who evaluated 48 genotypes, and Alam et al. (2024), who assessed 20 genotypes. Both studies demonstrated that traits such as fruit number per plant, fruit diameter, and average fruit weight per fruit exhibited high genotypic and phenotypic variability, despite the use of different genetic materials. Understanding the heritability of these traits is critical in designing effective breeding strategies in cayenne pepper, as it helps improve productivity and adaptability across diverse environmental conditions, thereby facilitating the development of superior, high-yielding, and stable cultivars.

The combination of high heritability and broad genotypic variability in traits such as days to anthesis, fruit diameter, fruit length, and average fruit weight indicates that these traits are largely governed by additive genetic effects. This implies that these traits are primarily governed by genetic factors and can be effectively selected in early generations (Hermanto et al. 2017; Ritonga et al., 2019; Qadri et al., 2020). Similar findings were reported by Farwah et al. (2020) and Panja et al. (2025), who also observed high heritability in traits including days to anthesis, fruit diameter, fruit number, and average fruit weight. Therefore, these traits represent promising targets for selection in cayenne pepper breeding programs aimed at enhancing quality and yield.

Of the 39 genotypes evaluated, the genotypes ‘Baja F1’, ‘Caman’, ‘Landung’, ‘Aka’, ‘Bali 77’, ‘Lajang’, ‘Laris’, and ‘Iggo’, exhibited high estimated yield (7.15-8.08 tons.Ha^{-1}). However, these cayenne pepper yields remain below the potential national productivity, which can reach up to 12 tons.Ha^{-1} (Syukur et al., 2010; Qosim et al., 2013). The low yield observed indicates the presence of limiting factors affecting crop productivity, stemming from both genetic and environmental influences. This is consistent with the findings of Susanti et al. (2023), who emphasized that crop productivity is strongly influenced by the interaction between the plant’s genetic potential and its environmental conditions. From a genetic perspective, improvement in a specific morphological trait may contribute to the enhancement of other yield-related traits, thereby serving as a valuable basis for selecting superior genotypes (Prihaningsih et al., 2023).

In addition to genetic factors, environmental conditions also play a crucial role in determining crop productivity. One of the key environmental factors is soil condition, particularly soil acidity (soil pH) (Sufardi et al., 2017). Low pH can increase exchangeable aluminum (Al^{3+}), which is toxic to plant roots and hinders the uptake of essential nutrients (Anas et al., 2024). Setiadi and Anira (2015) reported that when soil pH drops below 4, the concentrations of aluminum (Al) and iron (Fe) rise while phosphorus (P) availability declines, negatively affecting plant growth.

Climatic conditions during the study also influenced the yield obtained. The research period, which coincided with the onset of the dry season in August, resulted in water deficits during the flowering and fruit-setting stages. Water scarcity during these critical phases can lead to flower abortion and reduced fruit set. Conversely, increased rainfall in September to October led to higher humidity levels, which may have triggered the onset of plant diseases (Ridho, 2020). Both of these conditions imposed environmental stress that hindered the achievement of optimal yields.

In summary, the findings of this study emphasize that cayenne pepper productivity is influenced by the interaction between genetic potential and environmental factors. Plants with high genetic potential cannot express optimal yields if not supported by favorable environmental conditions, such as fertile soil, conducive climate, and proper crop management practices (Anggraini and Purnamaningsih, 2019). Therefore, the development of high-yielding and environmentally tolerant superior varieties represents a strategic approach for achieving sustainable improvements in chili production.

CONCLUSION

Research on 39 cayenne pepper genotypes showed that most generative traits, including days to anthesis, days to harvest, number of fruits per plant, fruit diameter, fruit length, pedicel length, and average weight per fruit, had broad genotypic and phenotypic variability and moderate to high heritability values, reflecting the dominance of genetic influences and good selection potential. In contrast, the traits of fruit weight per plant and fruit weight per plot showed narrow genotypic variability and low heritability, indicating greater environmental influences. These findings suggest that selection for traits with broad genotypic variability and high heritability could be an effective strategy in cayenne pepper breeding to improve productivity in suboptimal environments.

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