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Performance and yield stability of cayenne peppers (*Capsicum frutescens*) in multilocation trials in the Indonesian lowlands

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Abstract. *Sayekti TWDA, Syukur M, Hidayat SH, Maharijaya A, Sobir, Agustina K, Mareza E, Wahyudi A, Supriyanta B. 2024. Performance and yield stability of cayenne peppers* (Capsicum frutescens) *in multilocation trials in the Indonesian lowlands. Biodiversitas 25: 3008-3017.* Cayenne pepper (*Capsicum frutescens* L.) plant breeding is becoming an increasingly interesting topic due to various usages. The diversity of uses of chilies needs to be balanced with high production and good product quality so that it can meet market needs. This experiment aimed to evaluate the performance and plant diversity of eight elite lines and six commercial varieties of cayenne pepper (*C. frutescens*) in three different environments. The development of location-specific superior genotypes can be guided to create varieties suited to the targeted environment. This study was conducted in three locations (environments) namely “Lampung”, “Yogyakarta” and “Palembang”. The experiment was conducted using a Randomized Complete Block Design (RCBD) with three replications for each location. Analysis of yield stability was conducted using three methods, namely “Francis-Kanneberg”, “Finlay-Wilkinson” and “AMMI” methods. Among the three locations, the Lampung location experienced a very significant yield loss. This is thought to be due to disease attacks on the plantations. Some genotypes are more suitable for planting at one of the test locations compared to the other two locations. However, there are two genotypes that are stable at three locations based on the three analysis methods used. Genotypes "F1.323340" and "F1.285290” were observed to be stable and produced well at all test locations. Both genotypes can be recommended for planting in lowland environments.

Keywords: AMMI, biplot, chili pepper, high productivity, lowland

INTRODUCTION

Chili pepper is a horticultural commodity that belongs to the genus *Capsicum* and family Solanaceae. The *Capsicum* genus has many species (Muñoz-Concha et al. 2020). There are at least 43 species that have been registered, as stated by Barboza et al. (2022), five of which are widely cultivated and consumed. The five species are *Capsicum annuum* L., *C. frutescens* L., *C. chinense* Jacq., *C. baccatum* L., and *C. pubescens* Ruiz & Pav. (Jarret et al. 2019; Parry et al. 2021). Cayenne pepper (*C. frutescens*) is a type of chili with a spicy taste and distinctive fruit shape, that is now widely used for various purposes such as for food and medicine, and as an ornamental plant. Therefore, cayenne pepper plant breeding is becoming an increasingly interesting topic. Until now, chili has still been an essential commodity in high demand. Chili is widely used as the primary source of spicy taste, especially in Asia. However, currently, the use of chilies includes not only food ingredients but also for bio-pharmaceutical purposes (Dorantes et al. 2000; Perucka dan Materska 2001; Darmastuti et al. 2024) and as ornamental plants (Virga et al. 2020).

Chili production generally has many challenges due to environmental factors. To be released as a commercial variety, chili genotypes must have a superior character and adapt well to the targeted market environment. A superior variety is a variety that exhibit good performance, high yields, and stability in various environments (Dia et al. 2016) and seasons. This is due to the high demand for agricultural commodities; thus, expansion of planting area (extensification) is anticipated. The same principle applies to chili commodities (*Capsicum* spp.).

To obtain a genotype with high performance and promising yield, the breeder must consider the genetic potential of the targeted genotype (Peña-Yam et al. 2019). In addition to genetic considerations, environmental factors also play a crucial role, as the plant's phenotype is not solely determined by genetics but also influenced by the environment and the interaction between genetics and environment (Bavandpori et al. 2015). This interaction adds complexity to breeding activities. If the Genetic × Environment (GXE) interaction is not significant, all genotypes can exhibit stable performance in various environments (Cabral et al. 2017). However, when this GXE interaction is significant, variations in plant performance emerge in specific environments (Jayaningsih et al. 2020), posing challenges for breeders in recommending suitable genotypes. Various research indicates that chili plants may respond differently to drought (Macias-Bobadilla et al. 2020), light (Siahaan et al. 2023) etc., suggesting potential variation in their adaptation to changes in the environment. Exploring this phenomenon is essential, as it serves as a foundation for recommending genotypes suited to each environment, to enhance productivity (Sitaresmi et al. 2019). The development of location-specific superior genotypes can be guided to create varieties suited to environments, while those exhibiting superiority across diverse environments can be introduced as widely adaptable varieties (Hu et al. 2013). Testing in various planting locations is also called multilocation (multi-environment) testing. Multilocation tests study the level of adaptation of genotype effects to environmental variations through a combined analysis of variance with the main effects of genotype, environment and the interaction of Genotype and Environment (G×E). The level of stability of a genotype to various environmental conditions can be determined through a combined analysis of variance and stability.

In previous plant breeding activities, several plant genotypes (both hybrid and non-hybrid) that had superior characteristics had been obtained. If these genotypes are to be widely cultivated, it is necessary to test the adaptability of the plants. In this study, performance evaluation was carried out for each genotype at several locations representing different environmental conditions (lowland environment). This experiment aimed to evaluate the performance and stability of eight elite lines and six commercial varieties (hybrid and non-hybrid) of cayenne pepper (*C. frutescens*) in three different lowland environments as a basis for selecting a candidate for a new variety.

MATERIALS AND METHODS

Study area and genetic material

This study was conducted in three locations (environments). The first experiment was conducted at Politeknik Negeri Lampung, Rajabasa, Bandar Lampung (±110 m asl). Second evaluation conducted at Universitas IBA, Palembang, South Sumatera (±8 m asl). Third evaluation conducted at University of Pembangunan Nasional "Veteran" Yogyakarta, Special Region of Yogyakarta, Central Java (±150 m asl). Temperature and rainfall data at the three locations are presented in Table 1.

Fourteen genotypes of cayenne pepper consisting of eight collection lines (hybrid and non-hybrid) and six commercial varieties (hybrid and non-hybrid) (Table 2) were used in this experiment. The experiment was conducted using a Randomized Complete Block Design (RCBD) with three replications for each location. Each genotype was planted in a 6 m × 1 m crop beds (spacing of 50 cm × 50 cm, 24 plants per bed).

Procedures

Each genotype was sown in seedling trays for five weeks or until the plants had 5-7 true leaves. The seedling tray was placed in a shady area and not exposed to direct sunlight. Seedlings that were five weeks old were then transplanted into beds with a spacing of 50 cm × 50 cm (24 plants per bed). Maintenance activities included watering, replanting, fertilizing, weeding, and pest control.

Watering is conducted in the morning and evening. Replanting involves replacing dead plants one week after planting. Fertilization is carried out using NPK 16-16-16 with a concentration of 10 g per liter and a dose of 250 mL per plant by pouring it into each plant hole. Weeding is performed by manually removing weeds around the plant. Pest and disease control measures are implemented when necessary. Harvesting occurs when at least 80% of the first fruit has turned red in color. Plants are harvested each week for ten times during the planting period.

Observations were made on 10 sample plants selected randomly in each experimental unit. Observed characters include yield and non-yield characters. Non-yield characteristics observed include day to flowering, plant height, dichotomous height, dichotomous height, stem diameter, canopy width, leaf length, and leaf width. The yield-related traits observed include fruit length, pedicle length, fruit weight, fruit diameter, flesh thickness, weight of 1000 seeds, number of fruits per plant, and yield per plant.

Table 1. Temperature and rainfall data at three test locations

Month	Temperature (°C)			Rainfall (mm)		
	Yogyakarta	Lampung	Palembang	Yogyakarta	Lampung	Palembang
January	23.0-33.0	21.0-39.0	22.0-34.0	51-500	50-350	50-150
February	24.0-32.0	22.0-34.0	23.0-34.0	101-500	20-200	50-150
March	23.0-34.0	22.0-34.0	23.0-35.0	101-500	50-250	0-150
April	23.0-35.0	21.0-35.0	22.0-35.0	21-400	0-150	50-150
May	23.0-36.0	22.0-34.0	22.0-35.0	21-150	50-200	50-150
June	24.0-35.0	23.0-33.0	22.0-34.0	0-50	0-75	21-100
July	22.0-35.0	21.0-33.0	21.0-34.0	0-100	20-100	0-150
Average	23.9-33.7	23.4-33.0	23.5-33.0	0-500	75-350	0-450

Table 2. Genetic material of 14 cayenne pepper (*Capsicum frutescens*)

Code	Genotypes	Type of genotype
V1	F5.372340-7-7H-3	Non-Hybrid
V2	F5.372340-7-28H-11	Non-Hybrid
V3	F5.372340-7-28H-9	Non-Hybrid
V4	F11.385290-123-6-15-4-1-1-4-4-2	Non-Hybrid
V5	F1.373340	Hybrid
V6	F1.373372	Hybrid
V7	F1.372340	Hybrid
V8	F1.285290	Hybrid
V9	Rawita	Hybrid (Commercial)
V10	Feira	Non-Hybrid (Commercial)
V11	Bonita	Non-Hybrid (Commercial)
V12	Hiyung	Non-Hybrid (Commercial)
V13	OR212	Non-Hybrid (Commercial)
V14	Pulaipila Hijau	Non-Hybrid (Commercial)

Table 3. F-ratios used to test effects for combined randomized complete blocks experiments over location

Sources of variation	df	Mean square	F-Test
Location	l-1	M1	M1/M5
Rep (Location)	rl-1	M2	
Genotype	g-1	M3	M3/M5
Location x Genotype	gl-1	M4	M4/M5
Residual	rgl-1	M5	

Table 4. Stability analysis method used in multilocation tests

Sources	Parameter	Explanation
Francis and Kannenberg (1978)	(CV_i)	Stable (static) if $CV_i < \overline{CV_i}$ and $Yi > \overline{Yi}$
Finlay and Wilkinson (1963)	(b_i)	Stable (dynamic) if bi = 1.0
Gauch and Zobel (1988)	AMMI	The distance between the PC1 and PC2 value of the genotype to the center point of the axis. (The smaller the ASV value, the closer it is to the point (0,0), and the more stable the genotype)

Note: CV_i: Coefficient of Variance; $\overline{CV_i}$: Average of Coefficient of Variance (CV_i); b_i: Coefficient of regression; ASV: AMMI stability value

Data analysis

Data analysis includes Combined Analysis of Variance (Combined ANOVA) and analysis of stability. A combined analysis of variance was performed using PKBT-STAT and PBSTAT-GE. Data arrangements and processing was done using Microsoft Excel 365 software. Combined analysis of variance was done for all the observed traits but for analysis of stability only yield-related traits that used. The model for Combined ANOVA is shown in Table 3. Combined analysis of variance of randomize complete block design is estimated with a linear model as follows:

$$Y_{ijk} = \mu + E_i + B_{k(i)} + G_j + (GE)_{ij} + \varepsilon_{ijk};$$
$$(i = 1, 2; j = 1, 2, 3, \ldots, 14; k = 1, 2, 3)$$

Where:
Y_{ijk} : Observation in the *i*th environment
*j*th : Genotype
*k*th : Replication
μ : Overall mean
E_i : *i*th environment effect
$B_{k(i)}$: *k*th replication effect nested to the *i*th environment
G_j : *j*th genotype effect
$(GE)_{ij}$: Interaction effect between *i*th environment and *j*th genotype and ε_{ijk} is residual effect

Three methods were used for analysis of stability, i) based on coefficient of variation between location (CV) (Francis and Kanneberg 1978); ii) based on coefficient of regression (bi) (Finlay and Wilkinson 1963) and iii) AMMI (Gauch and Zobel 1988). The stability analysis method used in multilocation trials is shown in Table 4.

RESULTS AND DISCUSSION

Plant yield performance across three environments

In this study, 14 genotypes were tested: four non-hybrid genotypes, four hybrid genotypes and six commercial varieties (hybrid and non-hybrid). The experiment results in three locations (environments) showed differences in plant performance at each location. This is indicated by the significant effect of location factors on all the characters tested. The results of the Combined Analysis of Variance (Combined ANOVA) showed that genotype, environment and GxE interactions had a significant effect on the test characters (Table 5). The Coefficient of Variance (CV) from the experiment ranged from 2.82 to 12.89%. This CV value is less than 20%, which shows that the homogeneity of the test environment and the accuracy of observation and analysis are high (Peña-Yam et al. 2019). The conclusions drawn from the analysis results are valid.

The flowering age ranges from 38-64 days after planting (Table 6). The genotype with the earliest flowering age is "F1.373340" which starts flowering at 29 HST, while the genotype with the slowest flowering age is the genotype "F11.385290-123-6-15-4-1-1-4-4-2" (54 HST). The average flowering time of cayenne pepper appears to be different in different locations. The tested genotypes were observed to flower more quickly in the "Lampung" location, while the "Palembang" and "Yogyakarta" locations had an average flowering age that was not significantly different.

In this research, an evaluation was carried out on yield components, which included fruit characteristics (fruit length, fruit diameter, and fruit weight) and the number of fruit and fruit weight per plant. “Feira” had the most significant average fruit length (4.90-5.93 cm) and was stable in all test locations (Table 7). In contrast, the genotype with the smallest fruit length was the “Hiyung” variety. For the fruit length, the tested genotype appeared to have a longer fruit size in the Palembang location compared to other locations.

The test genotypes were also observed to have variations in fruit diameter when planted in different locations (Table 8). The fruit diameter in the "Lampung" location was observed to be narrower than in the Yogyakarta and Palembang locations. The genotype "F11.385290-123-6-15-4-1-1-4-4-2" has the largest fruit diameter in the Yogyakarta and Palembang locations (14.52 and 14.70 mm respectively). The genotype with the smallest fruit diameter is the genotype "F5.372340-7-28H-9".

Based on the fruit weight of the cayenne genotypes tested, planting in Yogyakarta showed the lowest fruit weight compared to the other two locations. However, it was not significantly different from the Lampung location (Table 9). The greatest fruit weight was owned by the genotypes "F11.385290-123-6-15-4-1-1-4-4-2" (2.07-3.92 g) and was stable at all test locations. The lowest fruit weight was owned by the "Hiyung" genotype, with an average of 0.88 g and 0.80 g in the Yogyakarta and Lampung locations respectively.

The chili genotypes tested showed different numbers of fruit per plant in the three locations (Table 10). The number of fruits per plant in the Lampung location showed the lowest yield with an average of 2.62-32.60 fruits when compared with the Yogyakarta and Palembang locations, showing averages ranging from 446.75-702.67 fruits and 351.17-887.89 fruits. The "Hiyung" genotype has the highest number of fruits per plant in the Yogyakarta and Palembang locations (702.67 and 887.89 fruits), while the genotype that has the lowest number of fruits per plant is the genotype "F11.385290-123-6-15-4-1-1-4- 4-2". An illustration of plant performance is shown in Figure 1.

Table 5. Combine analysis of variance several traits of cayenne pepper across three different locations

Characters	Mean square				
	Location	**Rep (location)**	**Genotype**	**Genotype X location**	**CV (%)**
Days to flowering (day)	525.77**	8.62ns	148.29*	66.62**	4.73
Plant height (cm)	2163.56*	200.00ns	459.78ns	228.94ns	9.41
Dichotomous height (cm)	22802.44**	12.70*	205.30**	56.5**	6.89
Stem diameter(mm)	251.12**	4.18ns	18.19*	7.61*	11.84
Canopy width (cm)	11879.98**	83.19ns	349.42ns	219.5**	10.02
Leaf length (cm)	254.08**	9.56**	9.71ns	14.96**	6.86
Leaf width (cm)	110.79**	0.57**	1.18ns	2.03**	5.00
Fruit weight (g)	4.85**	0.09ns	1.68*	0.75**	12.89
Fruit length (cm)	8.11**	0.05ns	1.60**	0.34**	5.58
Pedicle length (cm)	6.10**	0.44**	1.36**	0.25**	7.07
Fruit diameter (mm)	18.3**	0.50ns	32.30**	5.3**	7.06
Flesh thickness (mm)	3.79**	0.02ns	0.56**	0.10**	12.57
Weight of 1000 seeds (g)	99.68**	0.03ns	1.98**	0.82**	2.82
Number of fruits per plant	3925508.96**	152.60ns	48620.61ns	26867.58**	6.05
Yield per plant (g)	8629376.87**	1636.13ns	58323.57ns	61013.07**	7.05
Potential yield (ton/ha)	4464.25**	1.20ns	42.61ns	46.69**	10.21

Note: CV: Coefficient of Variance; *Significant at level of 5%; **Significant at level of 1%; ns: Not significant

Table 6. Days to flowering of cayenne peppers in three locations

Genotypes	Yogyakarta	Lampung	Palembang	Genotype means
	--- Days to flowering (days) ---			
F5.372340-7-7H-3	52.67abcd	40.67bc	57.00ab	50.11b
F5.372340-7-28H-11	55.67abc	40.33c	57.00ab	51.00ab
F5.372340-7-28H-9	49.33cdef	39.33c	55.00b	47.89bcd
F11.385290-123-6-15-4-1-1-4-4-2	54.33abc	47.00ab	62.33a	54.56a
F1.373340	44.00f	39.33c	41.00d	41.44f
F1.373372	45.33ef	43.33abc	42.00cd	43.56ef
F1.372340	44.00f	43.00abc	41.00d	42.67ef
F1.285290	47.67def	45.33abc	42.00cd	45.00def
Rawita	47.67def	43.67abc	40.00d	43.78ef
Feira	57.33ab	49.00a	48.33c	51.56ab
Bonita	47.00def	41.33bc	48.33c	45.56cde
Hiyung	51.33bcde	40.00c	55.33b	48.89bc
OR212	45.33ef	44.00abc	40.00d	43.11ef
Pulaipila Hijau	58.00a	48.00a	46.00cd	50.67b
Location means	49.98A	43.17B	48.24A	

Note: Numbers followed by the same capital letter in the same row and the same non-capital letter in the same column were not significantly different based on HSD 5% test

Table 7. Fruit length of cayenne peppers in three locations

Genotypes	Yogyakarta	Lampung	Palembang	Genotype mean
	--- Fruit length (cm) ---			
F5.372340-7-7H-3	4.62ab	4.12abc	4.94bcd	4.56bc
F5.372340-7-28H-11	4.32ab	4.16abc	5.17bc	4.55bc
F5.372340-7-28H-9	3.33de	4.69a	5.30ab	4.44bc
F11.385290-123-6-15-4-1-1-4-4-2	3.47cde	3.33de	4.72bcd	3.84e
F1.373340	4.29ab	3.87bcd	4.70bcd	4.29bcd
F1.373372	4.30ab	4.01abcd	4.58cd	4.30bcd
F1.372340	4.21ab	4.43ab	5.19bc	4.61b
F1.285290	4.01bcd	4.35abc	4.26de	4.21cde
Rawita	4.13bc	3.68cde	4.70bcd	4.17cde
Feira	4.90a	4.71a	5.93a	5.18a
Bonita	3.23e	3.95bcd	4.83bcd	4.00de
Hiyung	3.27e	3.08e	3.63e	3.33f
OR212	4.05bc	4.07abc	4.45d	4.19cde
Pulaipila Hijau	3.99bcd	3.98bcd	4.52cd	4.16cde
Location means	4.01B	4.03B	4.78A	

Note: Numbers followed by the same capital letter in the same row and the same non-capital letter in the same column were not significantly different based on HSD 5% test

Table 8. Fruit diameter of cayenne peppers in three locations

Genotypes	Yogyakarta	Lampung	Palembang	Genotype mean
	--- Fruit diameter (mm) ---			
F5.372340-7-7H-3	10.82cd	11.08ab	11.71c	11.20bc
F5.372340-7-28H-11	9.11def	7.68fg	10.81cde	9.20ef
F5.372340-7-28H-9	4.65g	8.23ef	10.27cde	7.72gh
F11.385290-123-6-15-4-1-1-4-4-2	14.52a	9.74abcdef	14.70a	12.99a
F1.373340	7.17f	9.14bcdef	9.02e	8.44fg
F1.373372	12.56abc	10.40abcd	10.55cde	11.17bc
F1.372340	11.18bcd	8.72def	9.53de	9.81de
F1.285290	11.00bcd	9.50abcdef	10.73cde	10.41cd
Rawita	13.02ab	10.82abc	12.23bc	12.03ab
Feira	10.18de	8.78cdef	10.44cde	9.80de
Bonita	12.77abc	11.04ab	13.88ab	12.56a
Hiyung	7.08f	5.92g	6.53f	6.51h
OR212	12.72abc	11.56a	11.28cd	11.86ab
Pulaipila Hijau	8.67ef	10.00abcde	8.86e	9.17ef
Location means	10.39A	9.47B	10.75A	

Note: Numbers followed by the same capital letter in the same row and the same non-capital letter in the same column were not significantly different based on HSD 5% test

Table 9. Fruit weight of cayenne pepper in three locations

Genotype	Yogyakarta	Lampung	Palembang	Genotype mean
	--- Fruit weight (g) ---			
F5.372340-7-7H-3	1.76cde	2.24a	2.79bcde	2.26cde
F5.372340-7-28H-11	1.23ef	1.38bc	2.87bcde	1.82ef
F5.372340-7-28H-9	1.52def	2.24a	2.67cde	2.14cde
F11.385290-123-6-15-4-1-1-4-4-2	2.94a	2.07ab	3.92a	2.98a
F1.373340	1.52def	1.78ab	1.69gh	1.66f
F1.373372	2.43abc	2.45a	2.10defgh	2.33cd
F1.372340	1.77cde	1.99ab	1.83fgh	1.86def
F1.285290	2.18abcd	2.37a	2.05efgh	2.20cde
Rawita	2.37abc	2.37a	2.58def	2.44bc
Feira	2.63ab	2.53a	3.55ab	2.91ab
Bonita	2.04bcde	2.22a	3.42abc	2.56abc
Hiyung	0.88f	0.80c	2.88bcd	1.52f
OR212	2.12abcd	2.35a	2.49defg	2.32cd
Pulaipila Hijau	1.89bcde	2.32a	1.44h	1.89def
Location means	1.95B	2.08B	2.59A	

Note: Numbers followed by the same capital letter in the same row and the same non-capital letter in the same column were not significantly different based on HSD 5% test

Table 10. Number of fruits of cayenne peppers in three locations

Genotypes	Yogyakarta	Lampung	Palembang	Genotype mean
	--- Number of fruits per plant ---			
F5.372340-7-7H-3	619.69^{bcd}	7.23^{a}	586.36^{b}	404.43^{b}
F5.372340-7-28H-11	612.33^{bcd}	2.81^{a}	581.78^{b}	398.97^{bc}
F5.372340-7-28H-9	589.53^{d}	14.38^{a}	492.94^{c}	365.62^{cde}
F11.385290-123-6-15-4-1-1-4-4-2	326.22^{f}	2.62^{a}	351.17^{g}	226.67^{g}
F1.373340	658.28^{abc}	12.92^{a}	493.50^{c}	388.23^{bcd}
F1.373372	674.06^{ab}	12.31^{a}	374.67^{efg}	353.68^{de}
F1.372340	661.61^{ab}	18.22^{a}	583.47^{b}	421.10^{b}
F1.285290	621.56^{bcd}	25.50^{a}	392.94^{efg}	346.67^{e}
Rawita	595.53^{cd}	7.25^{a}	409.11^{efg}	337.30^{e}
Feira	354.39^{f}	12.62^{a}	427.47^{de}	264.83^{f}
Bonita	642.11^{abcd}	32.60^{a}	484.11^{cd}	386.27^{bcd}
Hiyung	702.67^{a}	3.67^{a}	887.89^{a}	531.41^{a}
OR212	659.78^{ab}	15.55^{a}	363.50^{fg}	346.28^{e}
Pulaipila Hijau	446.75^{e}	13.96^{a}	420.44^{ef}	293.72^{f}
Location means	583.18^{A}	12.97^{C}	489.24^{B}	

Note: Numbers followed by the same capital letter in the same row and the same non-capital letter in the same column were not significantly different based on HSD 5% test

Figure 1. Performance of 14 genotypes of cayenne pepper

In general, plantations in the Lampung location have a lower number of fruits compared to other locations. This is thought to be due to a reasonably massive disease attack compared to other locations. Lampung plantings experienced 38,89-91,67% Pepper Yellow Leaf Curl Disease (PYLCD) infestation, while Palembang and Yogyakarta plantings experienced lower PYLCD infestations of 5.56-38.89%.

Based on the results, fruit weight per plant of all genotypes tested showed different appearances in all test locations (Table 11). Fruit weight per plant in the Lampung location showed the lowest fruit weight per plant compared to the other two locations. The genotypes "F1.323340", "F1.285290", "Rawita", "Feira", "Bonita", and "Pulaipila Hijau" had a stable average fruit weight per plant in the Yogyakarta and Palembang locations. This shows that the six genotypes are suitable for planting in both locations.

Genotypes "F5.372340-7-7H-3", "F5.372340-7-28H-11", "F5.372340-7-28H-9", "F11.385290-123-6-15-4- 1-1-4-4-2", "F1.372340", "Hiyung", and "OR212" had better fruit weight per plant when planted in the Palembang location compared to the Yogyakarta location. In contrast, the genotype "F1.373372" had a better fruit weight per plant when planted in the Yogyakarta location compared to the Palembang location. The "Hiyung" genotype had the lowest fruit weight per plant, ranging from 507.61 to 622.42 g.

Yield stability

Stability analysis was carried out for the yield-related traits (yield per plant) at three locations. The level of plant stability was estimated using three different methods. Stability analysis based on the method of Francis and Kanneberg (1978) is measured based on the coefficient of diversity (CV_i) and included in the concept of static stability. This method uses analysis based on the average influence of genotypes and stable genotypes determined by the narrow level of diversity between each environment (Sitaresmi et al. 2019).

The results of Francis and Kanneberg's stability analysis show four groups of plant stability levels. The results of the analysis are presented in Figure 2. The genotypes "F5.372340-7-7H-3", "F1.372340", "F1.285290" dan "Bonita" are in Group I, namely high yielded, consistent, and stable performance ($CV_i < \overline{CV_i}$ dan $Yi > \overline{Y_i}$). Group II consists of the genotypes "F1.373372", "Rawita", and "OR212" and Group IV consists of the genotypes "F5.372340-7-28H-11", "F11.385290-123-6-15-4 -1-1-4-4-2", while "Hiyung" is an unstable and inconsistent genotype. Group III which consists of the genotypes "F5.372340-7-28H-9", "F1.373340", "Feira" and "Pulaipila Hijau" is a consistent but unstable genotype. These genotypes have high and stable average productivity in the three test locations. In addition, the variability between test environments was low enough that these genotypes fell into the stable and consistent category.

These results indicate that the genotypes included in Group I are stable genotypes that can be cultivated at the test locations. Static stability criteria, one of which is Francis and Kanneberg stability, show that the variety is suitable and can be cultivated in various environments, so it is suitable to be released as a superior variety (Teressa et al. 2021).

Finlay-Wilkinson's (1963) stability methods are based on the linear regression coefficient of genotype (bi) and average yield (Y_i). A genotype is categorized as stable if it has a bi value that is not significantly different from one (bi=1.0), marginal environmental adaptive if bi<1.0, and optimum environmental adaptive if bi>1.0. A recapitulation of the Francis-Kanneberg and Finlay-Wilkinson's stability analyses is presented in Table 13. Based on the Finlay-Wilkinson stability criteria, only the "Hiyung" genotype is included in the marginal land adaptive genotype category, while the other genotypes are included in the stable category.

Stability analysis using the AMMI method is based on the AMMI Stability Value (ASV) which is described by the distance between the genotype and the center coordinate point (0.0) on the principal component biplot (PC1 and PC2). Based on the AMMI variance, it is known that two main components of interaction are significant, which shows that the interaction effect has been reduced to these two principal components (Table 12). Stable genotypes based on AMMI model 2 (AMMI II) stability analysis; it is known that there are four genotypes categorized as the stable category. These genotypes are genotypes "F5.372340-7-28H-9" (V3), "F1.372340" (V7), F1.285290 (V8), and Bonita (V11) (Figure 3). The four genotypes are close to the center of the coordinate axis (0,0) and within the curve formed.

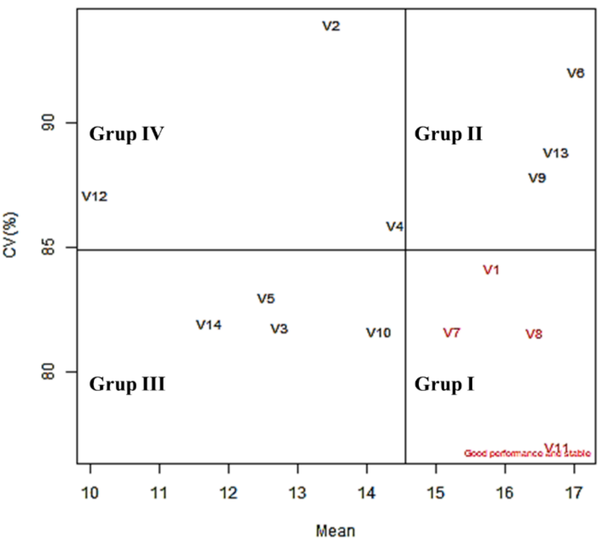

Figure 2. Relations between productivity (Yi) and Francis and Kannenberg stability parameters

Table 11. Yield per Plant of cayenne peppers in three locations

Genotypes	Yogyakarta	Lampung	Palembang	Genotype mean
	--- Fruit weight per plant (g) ---			
F5.372340-7-7H-3	855.24^{d}	10.91^{a}	906.50^{ab}	590.88^{abc}
F5.372340-7-28H-11	563.10^{hi}	4.10^{a}	950.06^{a}	505.75^{de}
F5.372340-7-28H-9	627.03^{gh}	25.69^{a}	772.47^{cde}	475.06^{ef}
F11.385290-123-6-15-4-1-1-4-4-2	763.61^{def}	4.85^{a}	851.06^{abc}	539.84^{cd}
F1.373340	664.71^{fgh}	15.50^{a}	727.12^{def}	469.11^{ef}
F1.373372	1,194.74^{a}	18.52^{a}	697.28^{def}	636.84^{a}
F1.372340	788.25^{de}	27.37^{a}	890.22^{ab}	568.61^{bcd}
F1.285290	1,022.42^{c}	40.27^{a}	773.04^{cde}	611.91^{ab}
Rawita	1,079.31^{bc}	12.67^{a}	752.88^{cde}	614.95^{ab}
Feira	757.86^{def}	18.65^{a}	806.64^{bcd}	527.72^{cde}
Bonita	971.01^{c}	52.58^{a}	838.64^{bc}	620.74^{ab}
Hiyung	507.61^{i}	3.04^{a}	622.42^{fg}	377.69^{g}
OR212	1,155.44^{ab}	29.28^{a}	682.75^{efg}	622.49^{ab}
Pulaipila Hijau	709.53^{efg}	22.80^{a}	579.61^{g}	437.31^{fg}
Location means	832.85^{A}	20.44^{C}	775.05^{B}	

Note: Numbers followed by the same capital letter in the same row and the same non-capital letter in the same column were not significantly different based on HSD 5% test

Table 12. The stability of cayenne pepper yield is based on several stability parameters

Genotypes	*Yi*	*CVi*		*bi*	
F5.372340-7-7H-3	15.81	84.2	S	1.11^{ns}	S
F5.372340-7-28H-11	13.49	93.92	-	0.94^{ns}	S
F5.372340-7-28H-9	12.75	81.79	-	0.84^{ns}	S
F11.385290-123-6-15-4-1-1-4-4-2	14.41	85.90	-	1.02^{ns}	S
F1.373340	12.56	83.03	-	0.86^{ns}	S
F1.373372	17.03	92.06	-	1.22^{ns}	S
F1.372340	15.24	81.63	S	1.02^{ns}	S
F1.285290	16.44	81.60	S	1.10^{ns}	S
Rawita	16.47	87.84	-	1.17^{ns}	S
Feira	14.18	81.64	-	0.96^{ns}	S
Bonita	16.75	77.01	S	1.08^{ns}	S
Hiyung	10.08	87.12	-	0.71^{*}	AM
OR212	16.73	88.84	-	1.16^{ns}	S
Pulaipila Hijau	11.73	81.95	-	0.80^{ns}	S

Note: Y_i: Yield at three locatin (ton/ha); CV_i: Coefficient of Variance; b_i: Genotype coefficient of regression; S: Stable; AM: Adaptive to Marginal land; *Significant at α=0.05; ns: Not significant at α=0.05

Table 13. AMMI stability for the yield of 14 genotypes of cayenne peppers at three locations (*Yi*)

Source	df	MS	F Value	Contribution (%)
Location (E)	2	6007.839	5110.76^{**}	-
Rep/Location	6	1.176	1.06^{ns}	-
Genotype (G)	13	42.589	0.99^{ns}	-
G×E	26	43.035	38.91^{**}	-
PC1	14	70.205	63.47^{**}	87.8
PC2	12	11.335	10.25^{**}	12.2
Residual	78	1.106	-	-

Note: df: Degree of freedom; MS: Means Square; PC: Principal Component; G×E: Interaction between genotype × location

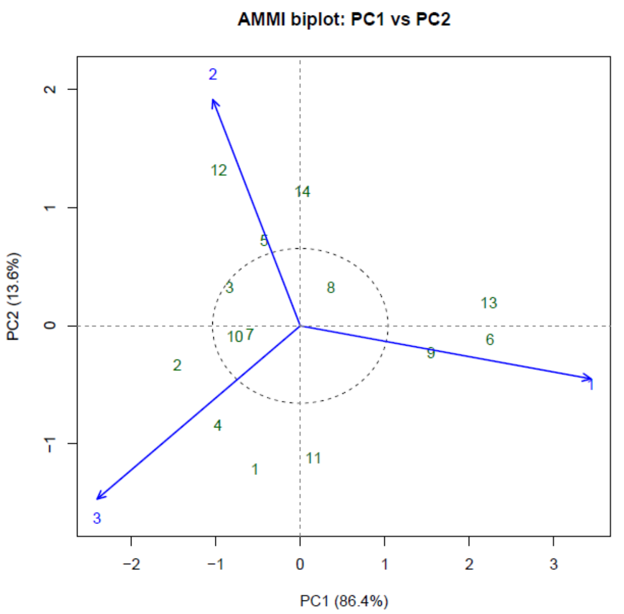

Figure 3. Biplot for AMMI II model between the second Principal Component (PC2) and the first Principal Component (PC1)

The stability analysis results using different methods produce different stability groups of productivity characteristics. Based on the three methods used, two stable genotypes were obtained at three test locations, namely the hybrid genotypes "F1.372340" (V7) and "F1.285290" (V8).

Discussion

The stability analysis produced different productivity character stability groupings when using different methods. However, some genotypes were deemed stable by multiple testing methods. Mohammadi et al. (2010) suggests that consistent results and associations between stability parameters can improve the accuracy of evaluating stable genotypes through predictions based on various methods. According to the method of Francis and Kannenberg (1978), four genotypes, namely "F5.372340-7-7H-3" (V1), "F1.372340" (V7), "F1.285290" (V8), and "Bonita" (V11), have shown high productivity with low inter-environmental variability. These genotypes are classified as stable and consistent in all three test locations. The Finlay and Wilkinson (1963) method also categorizes the same four genotypes as stable. According to multivariate AMMI method, it was found that the genotypes "F5.372340-7-28H-9" (V3), "F1.372340" (V7), "F1.285290" (V8), and "Rawita" (V10) categorized as a stable genotype. Based on the various methods used in this study, two genotypes were found to be stable in the three test locations, namely genotypes "F1.323340" (V7) and "F1.285290" (V8).

Multilocation tests are usually carried out to test the performance of potential new varieties that will be released to the market. The multilocation test studies the level of adaptation of a genotype to environmental variations through joint analysis of variance involving the main effects of genotype, environment and the interaction of genotype and environment (G×E).Through the combined analysis of variance, it is possible to determine the stability of a genotype in various environmental conditions (Ritonga et al. 2018; Teressa et al. 2021). The G×E value needs to be studied to understand its nature and level of contribution to make recommendations for the best cultivar suitable for each environment.

The test location is a lowland area that has environmental conditions that vary between Lampung (Lampung: 110 m asl; Palembang: 8 m asl; dan Yogyakarta: 150 m asl). The planting environment has a temperature range of 22-36°C in Lampung, 21-39°C in Palembang, and 21-35°C in Yogyakarta. These temperature conditions differ for each location, with the highest average daily temperature observed in Yogyakarta. This condition is suitable for chili planting, which requires full sunlight and relatively low temperatures.

Environmental factors generally influence quantitative characteristics, such as canopy morphology and plant productivity (Pimenta et al. 2016; Bartaula et al. 2019). However, in various studies, it has been reported that environmental factors greatly influence the flowering age of plants. Based on multilocation tests conducted by Sayekti et al. (2021) on green cayenne peppers (*C. annuum*) and Singh et al. (2016) it is known that the flowering age and harvest time of chili peppers are different at each test location. The flowering and harvest age can be influenced by several factors, including differences in temperature (Lin et al. 2021), humidity, light intensity, water, and nutrient availability (Ahmadi and Souri 2020; Pedroza-Sandoval et al. 2024). On the other hand, pest and disease attacks can also affect flowering time and harvest time in chilies (Sayekti 2021). This phenomenon explains why the chili genotypes that were tested should flowered more quickly in locations with higher temperatures and light intensity.

Different results were observed in this study. Chili plants planted in the Lampung location have a flowering period much faster than in other locations, even though the Lampung location has a higher altitude. This is thought to be due to a severe attack of Pepper yellow leaf curl disease in the Lampung location. PYLCD attacks in Lampung locations were 38.89-91.67%. Attacks of PYLCD in other locations were lower, only between 5.56-38.89%. PYLCD attacks have been reported to cause a significant reduction in yield in chili plants, affecting plant morphology and initiating flowering earlier (Sayekti 2024). According to this result, in this study, differences in flowering age at each location are more influenced by pest and disease attacks than differences in climatic conditions.

Red cayenne pepper plants (*C. frutescens*) generally have small and short fruit sizes with varied fruit diameters (narrow to wide). In general, the diversity among red cayenne pepper varieties is due to differences in genotype and not due to environmental differences. On the other hand, the intensity of sunlight, high temperatures, and nutrient status in the planting medium have also been reported to cause changes in leaf size (Dutta et al. 2017; Zakaria et al. 2020).

The use of different location characteristics in multilocation testing can also be used as a selection environment for potential new varieties. Besides getting an overview of plant performance in various types of environments, the information that will be obtained is the stability of the tested genotypes. A stable genotype is a genotype with good performance, high yields, and shows the same response to different environmental conditions (Dia et al. 2016). Stability analysis is carried out to see the stability of plants in several different environmental conditions. The results of the analysis showed that several plants were observed to have good stability in the three test locations. The stable genotype is a hybrid genotype generally responsive to environmental changes. According to (Sharma and Kumar 2017; Macias-bobadilla et al. 2020) hybrid genotypes have a significant response to cultivation inputs such as water and nutrients that are provided. On the other hand, hybrid genotypes generally have high yield potential. This means that differences in production in each environment do not have a significant effect (production stays high). These genotypes are then classified as high-yielding and stable genotypes.

In this research, several genotypes were obtained that were able to grow and have good productivity at each test location. These genotypes are "F5.372340-7-7H-3", "F1.323340", "F1.285290", "Rawita", "Feira", "Bonita", and "Pulaipila Hijau", of which two are collection hybrid genotypes ("F1.323340" and "F1. 285290") and stable based on all the methods tested. The test results showed that the two genotypes were superior and adaptive in different test environments, so they could be recommended for planting in lowland area in Indonesia.

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