CHAPTER III

Regional Trial and Stability Evaluation of New Mungbean (*Vigna Radiata* (L.) Wilczek) Lines Resistant to Powdery Mildew and Cercospora Leaf Spot Diseases through GGE Biplot Analysis

3.1 Abstract

This study evaluated the agronomic traits, disease resistance (Cercospora leaf spot; CLS and powdery mildew; PM), and yield stability of eight mungbean genotypes (SUPER5, CN84-1, P08, P12, P22, P24, CN3, and SUT1) across four environments (Nakhon Ratchasima, Chai Nat, Phitsanulok, and Phetchabun) and two seasons (rainy and dry season) during 2023-2024. Results indicated significant differences in yield, disease resistance, and agronomic performance across genotypes and locations. Among new lines, P22 demonstrated the highest yield across all environments with strong adaptability and stability, particularly in areas with high disease outbreak and P24 also exhibited high yield potential and good resistance to both CLS and PM, particularly in Phitsanulok and Phetchabun. The line P12, exhibiting delayed flowering and maturity, showed superior disease resistance and performed well in dry season. Line P08 showed consistent performance across environments, making it a suitable option for areas with variable growing conditions. The study also incorporated a multi-environment stability analysis using genotype plus genotype-by-environment interaction (GGE) biplot model, significant genotype environment interactions (GEI) were observed, P22 showed high yield and stability, particularly for pods/plant and yield. The highest overall stability was found in P08. The analysis revealed that Nakhon Ratchasima and Phetchabun were most representative for 100 seed weight and yield, while Phitsanulok and Chai Nat had more discriminative for yield and pods/plant. This study identified that P22 and P24 showing better adaptation and yield performance which classified them at ideal line.

3.2 Introduction

Mungbean [*Vigna radiata* (L.) Wilczek] is a vital legume crop widely cultivated across Asia and other tropical regions, particularly in countries such as India, China, and Thailand. It is valued for its high nutritional content and its ability to improve soil fertility through biological nitrogen fixation (Abbas et al., 2020; Ilyas et al., 2023). This nitrogen-fixing capacity makes mungbean highly suitable for crop rotation systems and as a green manure crop, contributing to enhanced soil health, reduced production costs, and more sustainable agricultural practices (Nair et al., 2013; Kim et al., 2015). In Thailand, major mungbean-growing regions include Chai Nat, Phetchabun, and Khon Kaen, where the crop is integrated into various cropping systems to improve soil fertility and farmer livelihoods (Udomsak, 2008; Office of Agricultural Economic, 2022). Mungbean is cultivated during the rainy, late rainy, and dry seasons. Due to its agronomic benefits and nutritional value, mungbean plays a critical role in sustainable food production systems. However, despite its significance, domestic production is insufficient to meet national demand. In 2021, Thailand imported 36,385 tons of mungbean while domestic consumption reached 109,446 tons, underscoring the fragility of the local supply chain and the need to boost national production capacity (Office of Agricultural Economics, 2021).

One of the key limitations to mungbean productivity in Thailand is the lack of improved varieties that are both high-yielding and adapted to local agroclimatic conditions. Compounding this issue is the prevalence of serious foliar diseases particularly PM and CLS which are among the most devastating diseases affecting mungbean (Pandey et al., 2018; Papan et al., 2021). These diseases cause substantial yield loss, especially under favorable environmental conditions, and hinder the overall growth of the mungbean crop (Barros et al., 2019). Cercospora leaf spot (CLS; caused by *Cercospora canescens*), can lead to yield losses of up to 96% under severe epidemic conditions (Pandey et al., 2018; Abbas et al., 2020; Ilyas et al., 2023). The disease impairs photosynthesis by damaging leaf tissues and chloroplasts, directly affecting plant health and productivity. Similarly, powdery mildew (PM; caused by *Sphaerotheca phaseoli*) and related fungi, can result in yield losses ranging from 50% to 100% at the seedling stage. The complete crop failure depending on environmental conditions and the crop stage (Papan et al., 2021).

While traditional disease management methods including fungicide application and cultural practices are commonly used, they are often costly, inconsistent, and environmentally unsustainable. The use of resistant varieties remains the most effective and environmentally sound approach to controlling PM and CLS in mungbean production (Pandey et al., 2018; Papan et al., 2021). However, resistance sources in mungbean germplasm remain limited, and their expression can vary depending on the environment. Advances in breeding technologies, including marker-assisted selection (MAS), have enabled the development of improved mungbean lines with dual resistance. Nonetheless, the yield potential, stability, and adaptability of these lines across diverse environments still require comprehensive evaluation (Papan et al., 2021).

Regional yield trials and stability assessments are thus crucial for identifying mungbean genotypes that combine high yield performance with durable resistance to PM and CLS. In Thailand, commercial varieties such as Kamphaeng Saen (KPS) 2, Chai Nat (CN) 72, CN84-1, and CN3 are known for high yield potential but remain susceptible to these diseases (Chueakhunthod, 2019). Therefore, this study aimed to evaluate the agronomic traits, yield performance, and stability of four newly developed mungbean lines P08, P12, P22, and P24 across multiple environments through regional yield trials. The goal is to identify superior genotypes suitable for varietal release that can offer farmers more reliable, productive, and disease-resilient options for mungbean cultivation.

3.3 Materials and methods

3.3.1 Plant materials and breeding procedure

In this study, a total of eight mungbean genotypes were used, and their special features and origins were provided in Table 3.1, including Thai certified varieties (CN3, CN84-1, and SUT1), SUPER5, P08, P12, P22, and P24. The SUPER5 line is resistant to PM and CLS and was developed by Pookhamsak et al. (unpublished data). The P08, P12, P22, and P24 lines were selected from backcross progenies of the recurrent parent CN84-1 and a resistant donor parent, which were developed from backcrossing between CN84-1 and double cross lines [(CN72×V4758) × (CN72×V4718)] × [(CN72×V4718) × (CN72×V4785)]. The resistant lines V4718, V4758, and V4785 originated from India, as shown in Figure 3.1.

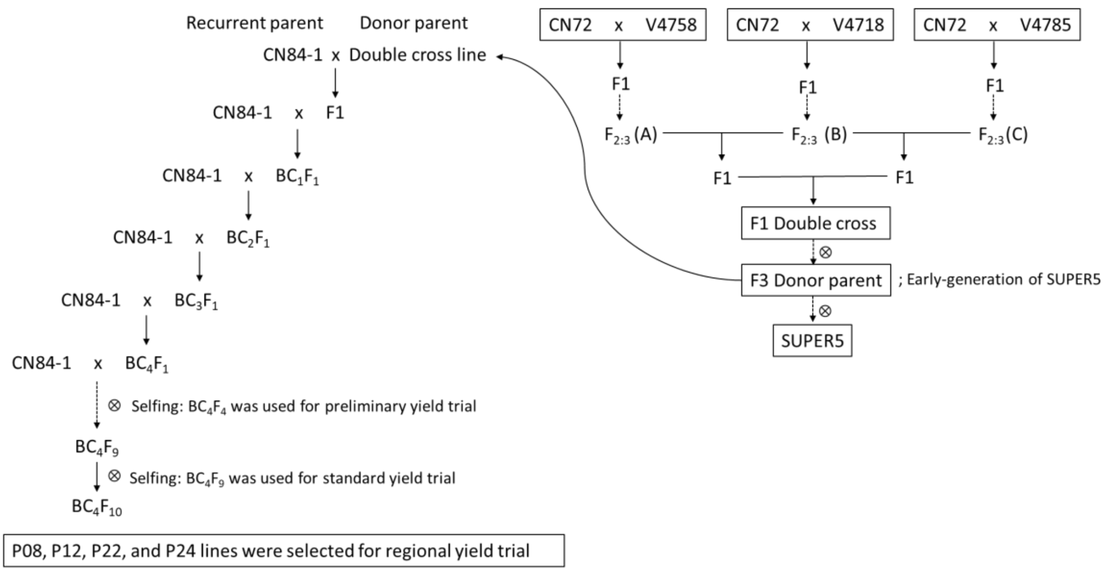


Figure 3.1 Pedigree of backcross progenies from a cross between CN84-1 and resistant double cross line.

Table 3.1 Pedigree and special features of eight mungbean genotypes used in this study.

Genotypes	Pedigree	Special features	Descriptions
SUPER5	Development from double cross lines [(CN72×V4758) × (CN72×V4718)] × [(CN72×V4718) × (CN72×V4785)]	High resistance to PM[1/] and CLS[2/]	The mungbean resistant line developed by Pookhamsak et al. (unpublished data)
CN3	Selection from mutated CN36	Large seed, high yield, uniform maturity	Thai certified varieties developed at Chai Nat Field Crops Research Center, Thailand
CN84-1	Selection from mutated CN36	Large seed, high yield, high percentage of carbohydrate	
SUT1	UTHONG1 x NP-29	High yield, pods borne above the canopy, moderate resistance to PM	The certified mungbean variety from Suranaree University of Technology (SUT), Thailand
P08	Selected from backcrossing between CN84-1 and double cross lines [(CN72×V4758) × (CN72×V4718)] × [(CN72×V4718) × (CN72×V4785)]	Large seed, uniform maturity, moderate resistance to PM and CLS	New resistant lines
P12		High yield, rather drought resistance, high resistance to PM, moderate resistance to CLS	
P22		High yield, uniform maturity, abundant pods, moderate resistance to PM and CLS	
P24		Large seed, uniform maturity, moderate resistance to PM and CLS	

[1/] powdery midew, [2/] Cercospora leaf spot

3.3.2 Regional yield trials

The regional trials were conducted to evaluate yield performance, agronomic traits, and resistance ability to PM and CLS under diverse environmental conditions. Four newly developed mungbean lines (P08, P12, P22, and P24) were tested and compared with the recurrent parent CN84-1 and check varieties CN3 and SUT1, as well as the disease-resistant line SUPER5. The experiments were carried out at four locations across Thailand: Chai Nat Field Crops Research Center at Chai Nat Province, Phetchabun Agricultural Research and Development Center at Phetchabun Province, Phitsanulok Seed Research and Development Center at Phitsanulok Province, and the SUT Farm at Nakhon Ratchasima province. The assessment of CLS disease was performed during July to October 2023, while the evaluation of PM disease was conducted from November 2023 to February 2024, across the same four experimental sites. The experimental information and conditions of these sites are presented in Table A.1 and Figure A.6-Figure A.13.

Each experimental field was divided into plots measuring 4 × 6 m per replication with row spacing is 0.5 m and plant spacing is 0.2 cm (total of 8 rows, with 30 plants per row), while the resistant line SUPER5 was planted in a single row for disease comparison. Border rows are planted around the experimental field with 4 rows, using a susceptible variety as a source of disease inoculums. Agronomic data were collected by randomly sampling 10 plants per replication per genotype to calculate the average values. The agronomic practices were implemented across all experimental locations. Prior to sowing, pre-emergence herbicide (alachlor) was applied to control weed growth. Carbofuran (3% G) was incorporated at a rate of 10 g per planting hole as a basal treatment for insect pest management. A compound fertilizer (N-P-K: 12-24-12) was applied at a rate of 30 kg/rai at planting. Ten days after emergence, seedlings were thinned to maintain two plants/hole. To control stem fly larvae, triazophos (40% EC) was sprayed at a concentration of 50 ml per 20 liters of water. At 25–30 days after sowing, an additional application of N-P-K fertilizer (12-24-12) at the same rate (30 kg/rai) was made, followed by hilling up around the base of the plants. Two months after sowing, triazophos (40% EC) was again applied at the same concentration to prevent pod borer infestation (*Maruca vitrata*). Weed control was performed manually as needed when weed pressure was high. Irrigation was provided once a week throughout the growing period.

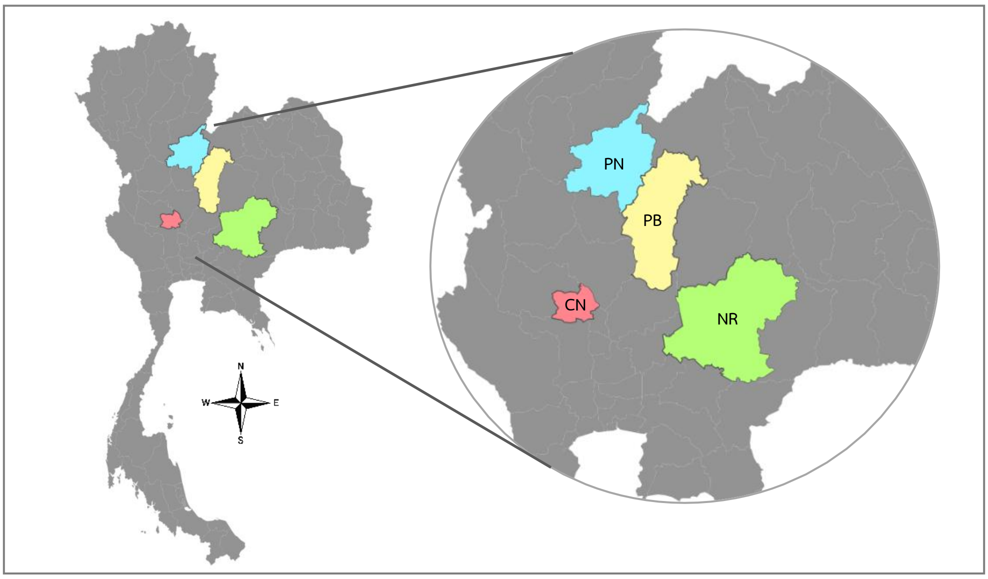


Figure 3.2 Location map of the experimental sites in Thailand, Abbreviation: NR = Nakhon Ratchasima, CN = Chai Nat, and PN = Phitsanulok, and PB = Phetchabun. Map created using pixel map generator (www.pixelmap.amcharts.com).

3.3.2.1 Agronomic traits and diseases scoring

The evaluation of agronomic traits and yield parameters was conducted according to the "Manual for recording mungbean research data" published by the Department of Agriculture (2018) and Chueakhunthod et al. (2020) as follows: Days to flowering: number of days from sowing to 50% of plants in the plot with first pod ripe. Days to maturity: counted from the planting date to the date when 50% of the plants in the plot have the first mature pod. Plant height (cm): measure from soil level to the highest point after the first harvest. Average of ten plants/plot. Lodging score: score the observation plants during the harvesting period based on the angle they lean away from the vertical position over 45°, where the scored indicated 1 = no lodging, 2 = lodging of 1-25% of the plot area, 3 = lodging of 26-50% of the plot area, 4 = lodging of 51-75% of the plot area, and 5 = lodging of more than 75% of the plot area. Branches/plant: number of pod-bearing branches with at least two nodes. Average of ten plants/plot. Clusters/plant: number of clusters having at least one fully grown pod at first harvest including both main stem and branches. Average of ten plants/plot. 100 seed weight (g): weight of 100 randomly selected seeds. Average of ten plants/plot. Pods/plant: number of pods from two harvests. Average of ten plants/plot. Seed weight/plant (g): total seed weight from two harvest times. Average of ten plants/plot. Pod length (cm): maximum length of ten pods (in case of curved pods, the longest straight line from the base to the tip of pod was measured). Average of ten plants/plot.

Seeds/pod: number of seeds/pod of ten pods. Average of ten plants/plot. Yield (kg/rai): calculated by converting the average grain yield in each plot to kg/rai. Each plot had a harvestable area of 24 m^2, and harvesting was conducted once when more than 80% of the plants reached physiological maturity, approximately 70 DAP.

3.3.2.2 Assessment of PM disease

The assessment of PM resistance during the dry season involves random evaluations conducted at individual plants within each plot. Specifically, 10 plants per plot, aged 55 and 65 DAP, were scored for PM resistance. The observations of resistance levels were divided into four categories (resistance 1.0-3.0, moderate resistance = 3.1-4.7, moderate susceptibility = 4.8-6.4 and susceptibility = 6.5-9.0). The evaluation using a scoring system outlined by Khajudparn (2009), as showed in Figure A.14.

3.3.2.3 Assessment of CLS disease

In the rainy season, evaluations are randomly conducted at the plants within each plot with 10 plants. Assessments occur when mungbean reach 55 and 65 DAP. The scale of CLS severity was divided into three categories (resistance = 1.0-2.5, moderate resistance = 2.6-3.4 and Susceptibility = 3.5-5.0) following the scoring system outlined by Chankaew (2009), as illustrated in Figure A.15.

3.3.2.4 Severity index (SI)

SI is a measurement used to quantify the intensity of a disease in plants. The SI helps to evaluate the effectiveness of disease management practices or the level of resistance in a particular variety. Calculate the severity of disease occurrence using the data of ten plants of disease in each plot. Use the formula developed by Asefa et al. (2016) for calculation.

$$\mathrm{SI}\ (\%) = \frac{\text{Summation of numerical rating}}{\text{No. plants examined} \times \text{Maximum disease score}}\ x\ 100$$

3.3.2.5 Area under the disease-progress curve (AUDPC)

AUDPC is a quantitative measure used to assess the progression of plant diseases over time. It represents the cumulative amount of disease development throughout the growing season or experiment, providing an overall picture of disease intensity. Calculated based on the SI using the method described by (Campbell & Madden, 1990) as follows:

$$\mathrm{AUDPC} = \sum_{\mathrm{i}=1}^{\mathrm{N_i}-1} \frac{(\mathrm{y_i} + \mathrm{y_{i+1}})}{2} (\mathrm{t_{i+1}} - \mathrm{t_i})$$

When: y_i = SI at the beginning of disease assessment.
y_i+1 = SI at the end of disease assessment.
t_i = time at the beginning of disease assessment.
t_i+1 = time at the end of disease assessment.

3.3.3 Data analysis

Data collected for each trait based on the Randomized Complete Block Design (RCBD) were analyzed. This included data on agronomic and disease resistance traits obtained with triplicate. Mean values for each trait were calculated separately for each location across replications. Subsequently, analysis of variance (ANOVA) was performed using SPSS for Windows Version 14.0 (Levesque, 2007). The combined analysis of variance across locations was conducted based on individual ANOVA from each location, following the method described by (Gomez & Gomez, 1984).

3.3.4 Construction of GGE biplot

The seed yields and yield components (pods/plant and 100 seed weight) collected were analyzed to assess yield stability. GGE biplot model, were applied (Gauch & Hugh, 2006). Yan et al. (2007) expanded the application of the GGE biplot to evaluate genotypes and pinpoint mega-environments. This approach emphasizes the genotype main effect (G) and GEI, while minimizing the influence of non-significant environmental main effects (E). The GGE biplot is generated by plotting the values of genotypes and environments along the first principal component (PC1) versus their corresponding values on the second principal component (PC2), which are derived through singular value decomposition (SVD) of environment-centered data using the given equation.

$$Y_{ij} = \mu + e_j + \sum_{n=1}^{N} \lambda_n \delta_{jn} + \varepsilon_{ij}$$

Where: *Yij* = mean response of i^{th} genotype (i = 1,..., *I*) in the j^{th} environment (j = 1,..., *J*), μ = grand mean, *N* = number of principal components retained in the model, e_j = environment deviations from the grand mean, $\boldsymbol{\lambda}_n$ = the eigen value of principal component analysis axis, **γ** = genotype PC score for axis, $\boldsymbol{\delta}_{jn}$ = environment PC score for axis, **ε**ij = the residual error term.

The optimal genotype was identified based on both mean performance and stability across different environments. Genotype evaluation was carried out and visualized through the "average environmental coordination/axis (AEC/AEA)" perspective of the GGE biplot, which allows for comparing the mean yield stability across environments within a mega-environment (Naık et al., 2022; Linus et al., 2023; Irfan et al., 2025). The 'symmetrical' GGE biplot analysis was conducted to evaluate the relationships among the test environments and to determine the proportion of variance attributable to GEI. The suitability of experimental sites was assessed using the 'discriminatory power and representativeness' perspective of the GGE biplot. Discriminatory power was reflected in the length of the environmental vector, while representativeness was indicated by the sharp angle between the environmental vector and the AEC (Tamang et al., 2022). Furthermore, the GGE biplot 'Which-won-where' approach was used to evaluate genotype performance under various experimental conditions and categorize test environments into distinct mega-environments. The stability analysis using the GGE biplot method was employed to evaluate stability using R software version 2.13.0 (Jompuk, 2008; R Development Core Team, 2019).

3.4 Results

3.4.1 The agronomic traits and CLS assessment during rainy season at Nakhon Ratchasima

For the agronomic traits and disease resistance of all mungbean genotypes during rainy season at Nakhon Ratchasima (Table 3.2), significant statistical differences were observed among the genotypes for certain traits. Days to flowering, days to pod maturity, seed weight/plant, CLS scoring and AUDPC showed statistically highly significant differences, whereas the other traits did not exhibit significant variation. Most newly developed lines generally flowered between 37.3 to 38.3 days after planting (DAP), which was comparable to the recurrent parent and the check varieties, except for line P12, which flowered later than all other genotypes at 44.3 DAP. For days to pod maturity, most lines were similar to the recurrent parent and the checks, except for P12, which exhibited a longer maturity period and demonstrated asynchronous maturity (<80% of the area reached maturity simultaneously). In terms of seed weight/plant, lines P22 and P24 produced 64.9-97.6% significantly higher weight compared to the recurrent parent and all check varieties. Meanwhile, lines P08 and P12 had seed weight that were comparable to the recurrent parent and check varieties. Under the rainy season conditions in this environment, no lodging issues were observed across all genotypes, and most lines matured uniformly. However, prolonged heavy rainfall during the harvest period (Figure A.6) resulted in reduced yield and high variability with 29.53% and 43.23% C.V. for seed weight/plant and yield, respectively. Nevertheless, under suboptimal environmental conditions, lines P22 and P24 showed adaptability to produce higher yields than the other genotypes. Agronomic traits assessments clearly indicated that the lines P22 and P24 were superior among genotypes, particularly in pods/plant, seed weight/plant, and yield. Notably, seed weight/plant and yield in P22 and P24 were at least 70% and 44% higher than the recurrent parent, respectively.

The CLS scores at 65 DAP in all new lines tended to be lower than those of the recurrent parent and the check varieties. Line P22 exhibited CLS scores comparable to the resistant line SUPER5. All new lines, except P12, showed resistance levels similar to SUPER5. The development of CLS in all new lines resulted in lower AUDPC scores compared to the recurrent parent and the check varieties.

Table 3.2 Agronomic traits and CLS resistance of new mungbean lines from yield trial in rainy season during July to October 2023 at Nakhon Ratchasima.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	CLS scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.59 c	R	259.38 c
CN84-1	36.9 b[4/]	53.1 bc	S	50.8	1.0	3.4	6.5	8.6	8.1	7.10	3.74 b	146.69	3.34 ab	MR	504.38 a
P08	38.0 b	53.8 bc	S	50.0	1.0	3.2	6.6	8.1	7.7	7.01	3.88 b	126.11	2.59 b	R	392.50 b
P12	44.3 a	57.3 a	A	59.9	1.0	3.8	6.1	8.7	7.8	6.09	2.95 b	104.55	2.68 b	MR	398.33 b
P22	37.3 b	55.0 ab	S	47.5	1.0	4.9	10.5	8.7	8.6	7.06	6.56 a	211.51	2.37 bc	R	381.25 b
P24	38.3 b	53.3 bc	S	50.6	1.0	4.5	11.3	8.6	8.6	6.74	6.40 a	215.25	2.46 b	R	375.00 b
CN3	38.0 b	54.3 abc	S	53.4	1.0	3.9	7.1	8.7	8.3	6.63	3.32 b	117.35	3.41 ab	MR	507.50 a
SUT1	38.3 b	52.5 c	S	58.7	1.0	4.7	7.5	8.5	8.6	6.26	3.52 b	112.61	3.95 a	S	582.13 a
F-test	**	**	N/A[5/]	ns	ns	ns	ns	ns	ns	ns	**	ns	**		**
C.V. (%)	2.7	2.1	N/A	14.0	0.0	22.7	37.0	4.3	7.7	6.06	29.53	43.23	4.17		8.79

[1/] Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. [2/] Score the observed plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. [3/] The scores of CLS severity at 65 DAP, where 1.0-2.5 = resistance, 2.6-3.4 = moderate resistance, and 3.5-5.0 = susceptibility. [4/] Data showing means, different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [5/] N/A = not available, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.2 The agronomic traits and CLS assessment during rainy season at Chai Nat

From Table 3.3 of agronomic traits and disease assessment of new mungbean lines P08, P12, P22, and P24 were compared to the recurrent parent CN84-1, check varieties (CN3 and SUT1) and resistant line (SUPER5) at Chai Nat, significant statistical differences were observed among the genotypes in nearly all traits, except for days to flowering, days to pod maturity, pod length, and AUDPC. The genotypes showed statistically highly significant differences in clusters/plant, pods/plant, and seeds/pod. While plant height, lodging, 100 seed weight, seed weight/plant, yield, and CLS scores exhibited significant difference.

Overall, line P22 exhibited the most favorable agronomic traits, particularly in yield, surpassing both the recurrent parent and the check varieties. Line P12 showed asynchronous maturity, unlike the other new lines which exhibited partial synchrony (80–90% of pods matured simultaneously), consistent with its tendency for longer days to flowering and pod maturity. The plant height of all new lines was not significantly different from the recurrent parent. Lodging was observed in recurrent parent and check varieties. However, the new lines exhibited no lodging. For clusters/plant, line P22 had the highest (9.6 clusters), significantly more than the recurrent parent and CN3 but comparable to the check variety SUT1. Lines P08, P12, and P24 showed comparable clusters/plant to the recurrent parent. In terms of pods/plant, line P22 produced the highest number (27.7 pods), significantly greater than the recurrent parent but comparable to SUT1 and CN3. Lines P12 and P24 also had more pods than the recurrent parent, while line P08 had similar pods number to the recurrent parent. Regarding seeds/pod, no significant differences were observed among the new lines and the recurrent parent, while lines P08 and P22 had significantly more seeds/pod than all check varieties. For 100 seed weight, lines P08, P12, and P24 were comparable to the recurrent parent and CN3. Although P12 had slightly lower seed weight but was not significantly different from the check varieties. In terms of seed weight/plant, line P22 recorded the highest value (15.12 g), 33-41% significantly greater than recurrent parent and check varieties. The other new lines did not differ statistically from recurrent parent and check varieties. For yield, line P22 produced the highest yield (399.60 kg/rai), exceeding the recurrent parent and check varieties by 43–60%. Line

P12 also outperformed the recurrent parent, yielding 321.53 kg/rai, approximately 28% higher. Lines P08 and P24 showed a tendency of 16% and 25% higher yields than the recurrent parent, respectively.

Regarding CLS scores at 65 DAP, lines P12, P22, and P24 had comparable scores to the resistant line SUPER5, with P12 showing the lowest score among the new lines. As CLS incidence was generally low under these environmental conditions, all genotypes exhibited low disease scores and were classified as resistant. The AUDPC values were consistent with the CLS scores at 65 DAP, with the new lines tending to have lower AUDPC values than the recurrent parent and SUT1, however, they were not significantly different.

Table 3.3 Agronomic traits and CLS resistance of new mungbean lines from yield trial in rainy season during July to October 2023 at Chai Nat.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	CLS scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.03 c	R	202.78
CN84-1	33.8[4/]	53.2	S	61.4 bc	2.3 a	6.5 c	15.7 d	9.3	11.0 a	6.68 a	10.75 b	249.45 c	1.88 a	R	288.33
P08	33.7	53.3	PS	56.1 c	1.0 b	6.6 bc	17.2 cd	8.9	10.9 a	6.45 ab	11.39 b	290.19 bc	1.73 ab	R	273.33
P12	35.3	59.7	A	68.5 ab	1.0 b	7.5 bc	20.9 bc	9.1	11.2 a	5.95 bc	12.67 ab	321.53 b	1.27 bc	R	226.67
P22	36.7	58.0	PS	56.1 c	1.0 b	9.6 a	27.7 a	8.7	10.6 ab	6.09 abc	15.12 a	399.60 a	1.53 abc	R	253.33
P24	33.3	54.0	PS	58.6 c	1.0 b	7.9 bc	20.8 bc	9.1	10.7 ab	6.39 ab	12.37 ab	312.78 bc	1.47 abc	R	246.67
CN3	34.3	55.3	S	59.9 bc	1.5 ab	8.1 b	19.1 bcd	8.6	9.9 c	6.27 ab	11.00 b	275.06 bc	1.68 ab	R	268.33
SUT1	34.7	57.8	PS	69.3 a	2.1 a	9.0 a	23.6 ab	9.2	10.2 bc	5.66 c	11.37 b	278.79 bc	1.81 ab	R	280.83
F-test	ns[5/]	ns	N/A	*	*	**	**	ns	**	*	*	*	*		ns
C.V. (%)	4.6	4.8	N/A	7.7	12.3	9.3	11.0	2.7	2.7	4.73	11.67	9.96	7.92		12.31

[1/] Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. [2/] Scores the observed plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. [3/] The scores of CLS severity at 65 DAP, where 1.0-2.5 = resistance, 2.6-3.4 = moderate resistance, and 3.5-5.0 = susceptibility. [4/] Data showing means different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [5/] N/A = not available, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.3 The agronomic traits and CLS assessment during rainy season at Phitsanulok

The results of the experimental cultivation of new mungbean lines P08, P12, P22 and P24 compared to the recurrent parent CN84-1, check varieties (CN3 and SUT1) and resistant line (SUPER5) at Phitsanulok were shown in Table 3.4. Most traits did not show clear differences among the genotypes, except for days to flowering, lodging and 100 seed weight, which showed statistically significant differences, while CLS scores and AUDPC showed highly significant differences.

Line P12 exhibited the longest day to flowering (44.3 days), while the other new lines had shorter days to flowering (36.0-38.0 days), which comparable to the recurrent parent and the check varieties. The maturity of P12 was classified as asynchronous (<80% of the area reached maturity simultaneously), whereas lines P22 and P24 exhibited synchrony maturity (>90% of the area reached maturity simultaneously), with greater uniformity than the recurrent parent and comparable to the check varieties. SUT1 showed the greatest plant height (98.6 cm), which resulted in a significantly higher lodging score than P24 and CN3. The new lines exhibited lodging scores not significant from the recurrent parent. For clusters/plant, P22 tended to be higher with 12.2 clusters than the recurrent parent CN84-1 (7.2 clusters) and the check varieties CN3 and SUT1 (7.1–10.1 clusters). Pods/plant for line P22 tend to have higher than other genotypes with 34.8 pods. The 100 seed weight of all new lines was similar to the recurrent parent but significantly higher than SUT1. No statistically significant differences were observed in seed weight/plant. However, lines P22 and P24 (23.61 and 18.13 g, respectively) tended to have 20-79% higher than the recurrent parent and check varieties. Consequently, yield of P22 and P24 (420.84 and 415.90 kg/rai, respectively) also tended to be higher. The highest yield was observed in P22, which exceeded the recurrent parent and check varieties by 18–33%.

For the CLS scores at 65 DAP, all new lines (1.67–2.33) and the recurrent parent CN84-1 (1.92) were classified as resistant. Line P12 had the lowest CLS score (1.67) among the new lines, lower than the recurrent parent (1.92) and significantly lower than all check varieties (2.67-2.83). Lines P08, P22, and P24 also tended to have lower CLS scores compared to the check varieties CN3 and SUT1, both classified as moderate resistant. For AUDPC, line P12 (265.00) recorded the lowest score among the new lines, comparable to the resistant line SUPER5 (216.81), and significantly lower than the recurrent parent CN84-1 (328.75) and all check varieties. The AUDPC values of P08, P22, and P24 (289.17–327.59) did not significantly differ from the recurrent parent but were significantly lower than the check varieties CN3 and SUT1 (381.67 and 387.50, respectively).

Table 3.4 Agronomic traits and CLS resistance of new mungbean lines from yield trial in rainy season during July to October 2023 at Phitsanulok.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	CLS scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.08 d	R	216.81 d
CN84-1	35.2 bc[4/]	58.0	PS	83.3	2.3 ab	7.2	20.8	10.6	12.0	7.0 a	15.10	346.71	1.92 bc	R	328.75 b
P08	36.0 bc	66.3	PS	74.6	1.8 ab	7.8	19.4	9.6	11.7	7.0 a	13.80	338.45	2.33 abc	R	327.59 b
P12	44.3 a	66.7	A	87.6	3.1 ab	7.6	18.7	9.5	11.5	6.68 a	12.66	330.22	1.67 c	R	265.00 cd
P22	38.0 b	59.7	S	71.9	2.7 ab	12.2	34.8	9.9	11.9	7.08 a	23.61	420.84	2.17 abc	R	314.26 bc
P24	36.0 bc	58.3	S	70.1	1.5 b	9.9	27.3	9.9	12.0	6.83 a	18.13	415.90	2.17 abc	R	289.17 bc
CN3	35.0 c	56.7	S	76.5	1.5 b	7.1	19.6	9.8	11.5	7.0 a	13.16	315.34	2.83 a	MR	381.67 a
SUT1	38.0 b	59.3	S	98.6	3.2 a	10.1	26.8	10.3	11.5	6.11 b	14.96	356.56	2.67 ab	MR	387.50 a
F-test	*	ns[5/]	N/A	ns	*	ns	ns	ns	ns	*	ns	ns	**		**
C.V. (%)	4.0	10.9	N/A	9.2	11.4	14.2	12.6	2.0	3.6	4.03	14.32	11.19	6.55		8.79

[1/] Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. [2/] Scores the observed plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. [3/] The scores of CLS severity at 65 DAP, where 1.0-2.5 = resistance, 2.6-3.4 = moderate resistance, and 3.5-5.0 = susceptibility. [4/] Data showing means, different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [5/] N/A = not available, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.4 The agronomic traits and CLS assessment during rainy season at Phetchabun

The results of the experimental cultivation of new mungbean lines at Phetchabun were shown in Table 3.5. Most traits did not show statistically significant differences among the genotypes, except for plant height and pod length, which exhibited significant differences. In contrast, lodging, CLS scores at 65 DAP and AUDPC showed highly significant differences.

The maturity of almost all genotypes was classified as synchrony (>90% of pods matured simultaneously), except for P24 and SUT1, which were classified as partial synchronous (80–90%). Most new lines had plant height comparable to the recurrent parent and check varieties, except for P08 (61.7 cm), which was shorter than both the recurrent parent CN84-1 (75.5 cm) and SUT1 (78.1 cm). Line P12 (81.6 cm) and variety SUT1 exhibited greater height and exhibited more lodging than other genotypes. Although clusters/plant and pods/plant did not show statistically significant differences, P22 recorded the highest values in both traits (7.4 clusters and 20.7 pods, respectively). For pod length, all new lines had similar average length (9.2 - 9.3 cm), which was shorter than CN84-1 (10.0 cm) but not significantly different from check varieties CN3 and SUT1 (9.2 and 9.6 cm, respectively). Lines P22 and P24 had the highest seed weight (11.60 and 11.61 g, respectively), showing a tendency to outperform other lines and varieties. Similar trends were observed in yield, with P22 and P24 (388.79 and 368.67 kg/rai, respectively) tending to produce 9-32% higher yields compared to the recurrent parent CN84-1 (339.54 kg/rai) and check varieties CN3 and SUT1 (293.92 and 295.83 kg/rai, respectively).

Most new lines had CLS scores at 65 DAP not significantly different from the recurrent parent, except for P24, which had lower scores (2.10), significantly lower than the recurrent parent (2.83) and all check varieties (3.45-3.59). Lines P12 and P24 were classified as resistant, similar to the resistant line SUPER5. While other new lines were classified as moderate resistance (P08 and P22). The CLS scores corresponded with AUDPC values other than SUPER5, line P24 recorded the lowest AUDPC (310.00), significantly lower than other new lines (350.00–388.33), the recurrent parent CN84-1 (382.50), and the check varieties CN3 and SUT1 (445.00 and 458.75, respectively). While other new lines had significantly lower AUDPC than the check varieties.

Table 3.5 Agronomic traits and CLS resistance of new mungbean lines from yield trial in rainy season during July to October 2023 at Phetchabun.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	CLS scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.05 e	R	204.58 e
CN84-1	32.7[4/]	45.7	S	75.5 ab	1.8 b	6.3	18.3	10.0 a	11.5	6.47	9.89	339.54	2.83 bc	MR	382.50 bc
P08	32.0	46.0	S	61.7 c	2.3 b	6.1	15.4	9.2 b	11.5	6.39	9.70	321.71	2.88 b	MR	388.33 b
P12	37.0	50.0	S	81.6 a	4.7 a	7.1	18.1	9.3 b	11.6	5.90	9.63	318.69	2.50 c	R	350.00 c
P22	36.7	52.3	S	67.6 bc	2.0 b	7.4	20.7	9.2 b	11.1	6.35	11.60	388.79	2.60 bc	MR	360.00 bc
P24	34.7	51.0	PS	71.3 abc	1.7 b	7.1	20.0	9.2 b	10.9	6.31	11.61	368.67	2.10 d	R	310.00 d
CN3	33.0	45.7	S	70.2 abc	1.7 b	6.6	15.7	9.2 b	11.2	6.56	9.09	293.92	3.45 a	MR	445.00 a
SUT1	34.8	48.5	PS	78.1 ab	3.8 a	6.8	17.1	9.6 ab	11.2	5.83	9.71	295.83	3.59 a	S	458.75 a
F-test	ns[5/]	ns	N/A	*	**	ns	ns	*	ns	ns	ns	ns	**		**
C.V. (%)	6.2	7.7	N/A	8.5	8.5	8.8	13.5	2.5	4.3	5.22	17.18	10.97	2.20		5.13

1/ Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. 2/ Scores the observed plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. 3/ The scores of CLS severity at 65 DAP, where 1.0-2.5 = resistance, 2.6-3.4 = moderate resistance, and 3.5-5.0 = susceptibility. 4/ Data showing means, different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). 5/ N/A = not available, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.5 The agronomic traits and CLS assessment during dry season at Nakhon Ratchasima

From the data presented in Table 3.6, significant differences were observed among mungbean genotypes in clusters/plant, seeds/pod, and yield, while highly significant differences were found in lodging, 100 seed weight, PM scores, and AUDPC.

The new mungbean lines were compared with the recurrent parent CN84-1 and the check varieties CN3 and SUT1. In terms of maturity, line P12 was classified as having partial synchrony (80–90% of pods matured simultaneously), similar to SUT1, whereas the other genotypes were classified as synchrony (>90%). Plant height did not differ significantly among genotypes; however, line P12 tended to be taller than the other new lines. Lodging was not observed in most genotypes, except in SUT1, which showed lodging issue. Line P12 produced significantly more clusters/plant (6.3 clusters) than CN84-1 (4.6 clusters) and was comparable to SUT1. Other new lines exhibited 5.0–5.3 clusters, which tend to be higher than CN84-1. Lines P12 and P22 showed a tendency for higher pods/plant (13.5 and 13.7 pods, respectively) than CN84-1 (10.7 pods). For seeds/pod, all new lines were comparable to the recurrent parent, but line P12 (10.7 seeds) had a significantly higher value than CN3 and SUT1 (9.1 and 8.9 seeds, respectively). For 100 seed weight, the four new lines were similar to both the recurrent parent and check varieties, except for line P08, P22 and P24, which had significantly higher 100 seed weight (6.45 - 6.68 g) than variety SUT1. In seed weight/plant, lines P12 and P22 tended to have higher values (8.08 and 7.03 g, respectively) than the other genotypes. In terms of yield, line P12 produced a significantly higher yield than CN84-1, with an increase of 28.9%, and exceeded the check varieties (CN3 and SUT1) by 20.8 - 29.7%. Lines P08, P22, and P24 exhibited yields not significantly different from both the recurrent parent and SUT1, while P22 resulted significant higher yields than variety CN3.

The PM scores at 65 DAP indicated that all four new lines and SUT1 exhibited moderate resistance. The recurrent parent CN84-1 and CN3 showed higher disease severity and was classified as moderately susceptible. The AUDPC followed a similar trend, showing no statistically significant differences among the new lines, the recurrent parent, and the check varieties. However, the resistant line SUPER5 exhibited the lowest AUDPC and was classified as resistant.

Table 3.6 Agronomic traits and PM resistance of new mungbean lines from yield trial in dry season during December 2023 to March 2024 at Nakhon Ratchasima.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	PM scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.23 c	R	123.69 c
CN84-1	41.0[4/]	57.3	S	47.0	1.3 bc	4.6 b	10.7	9.2	10.5 ab	6.53 ab	6.23	194.64 bc	5.24 ab	MS	479.63 ab
P08	39.7	56.7	S	49.7	1.0 c	5.0 ab	12.7	8.9	9.4 bc	6.68 a	6.61	209.94 bc	4.43 ab	MR	532.41 ab
P12	40.7	57.7	PS	53.3	1.5 bc	6.3 a	13.5	8.9	10.7 a	6.18 bc	8.08	250.84 a	4.52 ab	MR	539.81 ab
P22	40.0	57.0	S	49.4	1.3 bc	5.3 ab	13.7	8.6	9.7 abc	6.65 ab	7.30	234.00 ab	4.65 ab	MR	543.52 ab
P24	40.0	56.7	S	46.2	1.3 bc	5.0 ab	10.9	8.4	9.7 abc	6.45 ab	6.72	209.15 bc	3.14 b	MR	460.19 ab
CN3	39.3	55.7	S	49.7	2.0 b	4.5 b	10.8	8.5	9.1 c	6.87 a	6.05	193.44 c	5.76 a	MS	587.96 a
SUT1	37.0	55.0	PS	54.5	2.8 a	6.3 a	14.5	8.9	8.9 c	5.81 c	6.48	207.68 bc	4.77 ab	MR	395.37 b
F-test	ns[5/]	ns	N/A	ns	**	*	ns	ns	*	**	ns	*	**		**
C.V. (%)	8.5	7.3	N/A	11.9	8.6	13.9	27.7	3.5	6.7	3.84	10.95	9.53	7.16		18.29

[1/] Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. [2/] Scores the observed plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. [3/] The scores of PM severity at 65 DAP, where 1.0-3.0 = resistance, 3.1-4.7 = moderate resistance, and 4.8-6.4 = moderate susceptibility, 6.5-9.0 = susceptibility. [4/] Data showing means, different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [5/] N/A = not available, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.6 The agronomic traits and CLS assessment during dry season at Chai Nat

According to the data presented in Table 3.7 from the experimental cultivation at Chai Nat, most agronomic traits showed non-significant differences among mungbean genotypes. However, 100 seed weight, PM scores, and AUDPC exhibited highly significant differences.

When compared with the recurrent parent CN84-1 and the check varieties CN3 and SUT1. All genotypes except P12 classified as synchrony (>90%). Line P12 exhibited partial synchrony (80–90% of pods matured simultaneously), which corresponded with it delay days to flowering (63 days). Lodging issue was not observed in this trial; most genotypes showed less than 25% lodging within the cultivation area. For 100 seed weight, most new mungbean lines had weights similar to the recurrent parent CN84-1 and the check variety CN3, except for P12, which showed a lower weight than all other genotypes. In other agronomic traits, the new lines showed favorable tendencies compared to the recurrent parent and check varieties. For the clusters/plant, line P12 tends to produce higher clusters/plant among all genotypes with 9.3 clusters followed by P24 with 8.6 clusters. Similarly, lines P12, P22, and P24 showed a tendency of higher values for pods/plant and seed weight/plant (20.24-21.3 pods and 11.93-12.98 g, respectively) compared to the recurrent parent and check varieties. Consequently, these three lines exhibited promising yield levels, with yields of 327.34, 329.29, and 305.87 kg/rai, respectively.

The PM scores at 65 DAP indicated that PM was violent under the environmental conditions of Chai Nat, resulting in susceptibility across new lines, recurrent parent and check variety CN3. Nevertheless, the new lines tended to have lower PM scores than the recurrent parent and check variety CN3, ranging from 7.03 to 7.81. Notably, line P08 had a significantly lower PM score than the recurrent parent. Similarly, AUDPC in lines P08 and P12 were significantly lower than those of the recurrent parent and tended to be lower than CN3.

Table 3.7 Agronomic traits and PM resistance of new mungbean lines from yield trial in dry season during December 2023 to March 2024 at Chai Nat.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	PM scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.24 d	MR	506.33 d
CN84-1	40.2[4/]	59.3	S	71.6	1.3	7.2	17.1	9.6	11.6	6.79 a	11.57	261.78	8.06 a	S	1393.21 a
P08	40.7	59.7	S	70.3	1.0	6.8	17.3	9.5	12.2	6.53 a	11.29	294.45	7.03 bc	S	1236.21 bc
P12	41.7	63.0	PS	69.8	1.7	9.3	21.3	9.2	11.8	5.72 c	12.77	327.34	7.50 ab	S	1231.48 bc
P22	41.0	58.7	S	64.4	1.0	8.0	20.9	9.4	12.1	6.46 a	12.98	329.29	7.81 a	S	1322.74 ab
P24	40.3	57.7	S	63.4	1.0	8.6	20.4	9.2	11.6	6.63 a	11.93	305.87	7.41 ab	S	1289.51 ab
CN3	39.7	59.3	S	65.1	1.2	6.9	17.6	9.4	11.7	6.74 a	11.83	293.33	7.73 ab	S	1316.70 ab
SUT1	39.5	58.3	S	72.7	1.8	8.0	19.7	9.8	11.5	6.09 b	11.89	298.44	6.68 c	S	1140.53 c
F-test	ns[5/]	ns	N/A	ns	ns	ns	ns	ns	ns	**	ns	ns	**		**
C.V. (%)	4.6	3.6	N/A	21.9	14.0	17.0	15.4	5.3	8.3	2.75	12.26	10.51	1.03		4.77

[1/] Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. [2/] Scores the observation plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. [3/] The scores of PM severity at 65 DAP, where 1.0-3.0 = resistance, 3.1-4.7 = moderate resistance, and 4.8-6.4 = moderate susceptibility, 6.5-9.0 = susceptibility. [4/] Data showing means different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [5/] N/A = not available, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.7 The agronomic traits and CLS assessment during dry season at Phitsanulok

The results of the experimental cultivation of new mungbean lines P08, P12, P22, and P24 during dry season at Phitsanulok have been presented in Table 3.8. Most agronomic traits showed non-statistically significant differences among genotypes, except for 100 seed weight, which differed highly significantly.

When compared with the recurrent parent CN84-1 and the check varieties CN3 and SUT1, most genotypes exhibited synchrony maturity (>90% of the area reached maturity simultaneously), except for line P12, which showed partial synchrony (80–90%), P12 also tended to produce more clusters/plant and pods/plant than the recurrent parent. In terms of 100 seed weight, line P08 exhibited 7.13 g, which was comparable to the recurrent parent CN84-1 (7.26 g) and significantly higher than the check variety SUT1 (5.66 g). For yield, lines P08 and P24 tended to produce higher yields than both the recurrent parent and the check varieties, with the yields of 320.59 and 313.02 kg/rai, respectively. All new mungbean lines possessed distinct superior agronomic traits. However, line P08 tends to have higher seed weight/plant and yield than the recurrent parent CN84-1 (8.89 g and 299.52 kg/rai, respectively), with an average 9.64 g and 320.59 kg/rai, which was the highest among all genotypes.

For PM scores at 65 DAP, the environmental conditions at Phitsanulok were not conducive to PM development and less symptoms were observed. All genotypes were classified as resistant. The PM scores of new mungbean lines did not differ significantly among genotypes. However, line P24 showed the lowest PM score among the new lines (1.15), while the resistant control line SUPER5 showed no disease symptoms. The AUDPC followed a similar trend with PM scores, all four new lines exhibited lower AUDPC than the recurrent parent CN84-1.

Table 3.8 Agronomic traits and PM resistance of new mungbean lines from yield trial in dry season during December 2023 to March 2024 at Phitsanulok.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	PM scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.00	R	222.00
CN84-1	40.5[4/]	61.0	S	57.8	1.0	4.4	14.1	9.6	10.9	7.26 a	8.89	299.52	1.85	R	316.67
P08	40.3	60.0	S	49.4	1.0	4.9	13.5	9.5	10.8	7.13 ab	9.64	320.59	1.78	R	309.00
P12	41.3	60.7	PS	57.3	1.0	5.6	15.4	9.2	11.0	6.43 d	8.85	282.84	1.30	R	255.56
P22	39.3	60.7	S	50.2	1.0	4.6	13.6	9.2	10.9	6.71 cd	9.12	298.68	1.55	R	283.80
P24	39.0	60.0	S	50.3	1.0	4.3	12.5	9.3	10.8	6.81 bcd	9.44	313.02	1.15	R	238.89
CN3	38.3	59.7	S	54.5	1.0	5.5	14.6	9.2	10.6	7.07 abc	9.39	298.56	2.09	R	343.62
SUT1	38.5	58.7	S	57.3	1.0	5.3	16.7	9.2	10.6	5.66 e	9.64	293.13	1.11	R	234.72
F-test	ns[5/]	ns	N/A	ns	ns	ns	ns	ns	ns	**	ns	ns	ns		ns
C.V. (%)	3.0	1.8	N/A	8.6	0.0	16.9	15.1	3.1	4.7	3.10	16.34	17.01	11.98		20.11

[1/] Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. [2/] Scores the observed plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. [3/] The scores of PM severity at 65 DAP, where 1.0-3.0 = resistance, 3.1-4.7 = moderate resistance, and 4.8-6.4 = moderate susceptibility, 6.5-9.0 = susceptibility. [4/] Data showing means, different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [5/] N/A = not available, ns = not significant, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.8 The agronomic traits and CLS assessment during dry season at Phetchabun

The results of the experimental cultivation of new mungbean lines P08, P12, P22, and P24 during the dry season at Phetchabun are presented in Table 3.9. Most agronomic traits showed non-statistically significant differences among genotypes. However, days to flowering and lodging showed significant differences, while 100 seed weight, PM scores, and AUDPC showed highly significant differences.

When compared to new mungbean lines with the recurrent parent CN84-1 and the check varieties CN3 and SUT1, line P12 exhibited the longest duration to flowering at 48.7 days, which also led to a longer duration to maturity (64.3 days). The remaining new lines had days to flowering and days to maturity ranging 43.0-44.3 days and 61.7 to 63.0 days, respectively. In terms of maturity classification, line P12 exhibited partial synchrony (80–90%), similar to CN3, while the other genotypes displayed synchronous maturity (>90% of the area reached maturity simultaneously). Line P12 produced the highest clusters/plant (7.9 clusters) and pods/plant (19.7 pods), showing a tendency to outperform other genotypes. For 100 seed weight, lines P08, P22, and P24 were comparable to the recurrent parent CN84-1 and check variety CN3. Regarding seed weight/plant and yield, all new mungbean lines tended to produce higher values than both the recurrent parent and the check varieties, with yields ranging from 312.95 to 337.88 kg/rai.

For the PM scores at 65 DAP, line P12 exhibited the lowest PM score among the new lines, with a lower score than both the recurrent parent and the check variety CN3. The other lines also showed scores lower than the recurrent parent, but they are not significantly different. Lines P12, P22, P24, and the variety SUT1 were classified as moderately resistant, whereas CN84-1 and CN3 were categorized as moderately susceptible. For AUDPC values, lines P12, P22, and P24 exhibited lower values than both the recurrent parent CN84-1 and check variety CN3. The AUDPC value of line P08 was lower but not significantly different from that of the recurrent parent. These results clearly indicated that the new mungbean lines demonstrated better resistance to PM compared to the recurrent parent.

Table 3.9 Agronomic traits and PM resistance of new mungbean lines from yield trial in dry season during December 2023 to March 2024 at Phetchabun.

Genotypes	Days to flowering	Days to maturity	Maturity[1/]	Plant height (cm)	Lodging[2/]	Clusters/plant	Pods/plant	Pod length (cm)	Seeds/pod	100 seed weight (g)	Seed weight/plant (g)	Yield (kg/rai)	PM scores[3/]		AUDPC
SUPER5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.31 d	R	256.17 e
CN84-1	43.3 b[4/]	61.5	S	66.6	1.3 b	7.4	17.7	9.1	10.2	7.30 a	11.03	271.34	5.72 a	MS	824.85 a
P08	44.0 b	63.0	S	68.5	1.3 b	7.0	18.6	9.3	11.2	7.51 a	13.21	337.88	5.20 a	MS	731.48 ab
P12	48.7 a	64.3	PS	68.4	3.0 a	7.9	19.7	8.8	10.3	6.81 b	12.08	315.78	4.08 bc	MR	575.93 cd
P22	43.0 b	61.7	S	62.5	1.0 b	6.4	18.6	9.0	10.5	7.36 a	12.11	312.95	4.67 ab	MR	670.37 bc
P24	44.3 b	63.0	S	65.6	1.7 b	7.2	18.9	8.9	10.4	7.23 a	11.92	325.72	4.71 ab	MR	688.62 bc
CN3	41.7 b	60.3	PS	66.9	1.8 ab	6.4	18.3	8.8	10.3	7.27 a	11.62	298.63	5.16 a	MS	739.71 ab
SUT1	44.7 b	61.2	S	61.1	1.8 ab	7.3	18.7	9.4	10.8	6.73 b	11.03	282.77	3.46 c	MR	498.77 d
F-test	*	ns[5/]	N/A	ns	*	ns	ns	ns	ns	**	ns	ns	**		**
C.V. (%)	4.5	2.4	N/A	7.0	12.3	11.2	11.0	3.1	4.0	2.95	11.57	12.50	2.96		10.32

[1/] Maturity stages including synchrony (S): more than 90% of pods mature simultaneously at the first harvest, partial synchrony (PS): 80–90% of pods mature simultaneously, and asynchrony (A): less than 80% of pods mature simultaneously. [2/] Scores the observed plants based on the angle leaning away over 45°, where 1 = no lodging, 2 = lodging of 1-25% of area, 3 = lodging of 26-50% of area, 4 = lodging of 51-75% of area, and 5 = lodging more than 75% of area. [3/] The scores of PM severity at 65 DAP, where 1.0-3.0 = resistance, 3.1-4.7 = moderate resistance, and 4.8-6.4 = moderate susceptibility, 6.5-9.0 = susceptibility. [4/] Data showing means, different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [5/] N/A = not available, * = significant at $P \le 0.05$; ** = highly significant at $P \le 0.01$, and ns=non-significant at $P > 0.05$

3.4.9 Combined variance analysis for yield of mungbean genotypes

The combined variance analysis of seven mungbean genotypes across four experimental locations and two seasons is presented in Table 3.10, including the experimental fields in Nakhon Ratchasima (dry season), Chai Nat (rainy and dry seasons), Phitsanulok (rainy season), and Phetchabun (rainy and dry seasons). The experimental fields in Nakhon Ratchasima (rainy season) and Phitsanulok (dry season) were excluded from the combined analysis due to excessive variation. The results demonstrated that plant yield in the six fields was markedly affected by genotype (G) and location (L) with, although season (S) and their interactions (G × L, G × S, and G × L × S) exhibited non-significant effects.

The mungbean cultivated in Phitsanulok during the raining season demonstrated the highest yield, averaging 360.57 kg/rai, which was considerably superior to yields from other locations, exceeding them by 18-68%. This may have resulted from the lack of substantial rainfall during the harvesting time (Figure A.12), in contrast to other areas cultivated in the same season. Alternatively, it may be ascribed to more advantageous environmental conditions for mungbean cultivation relative to other locales and seasons. The average yield of all mungbean genotypes was 303.95 kg/rai. The yields of the new mungbean lines P12, P22, and P24 were significantly better than the recurrent parent CN84-1, whereas P08 exhibited non significantly different from the recurrent parent. Line P22 achieved the highest average yield of 347.58 kg/rai across six environments, surpassing the recurrent parent CN84-1 by 24% (279.95 kg/rai), while line P24 obtained 323.02 kg/rai, which is 15% larger than the recurrent parent. Nakhon Ratchasima (dry season) and Chai Nat (rainy season) showed significant differences in yield among genotypes, with average yields of 214.24 kg/rai and 306.64 kg/rai, respectively. Line P12 had the highest yield at Nakhon Ratchasima (250.84 kg/rai), while P22 had the highest yield at Chai Nat (399.60 kg/rai). Other new lines also exhibited higher or comparable yields relative to the recurrent parent and all check varieties. Although, yields in Chai Nat (dry season), Phitsanulok (rainy season), and Phetchabun (rainy and dry seasons) were not significantly different among genotypes, the new lines tended to produce higher yields than both the recurrent parent and all check varieties.

Table 3.10 Combined analysis of yield (kg/rai) of seven mungbean genotypes across four environments and two seasons.

Genotypes	Nakhon Ratchasima	Chai Nat		Phitsanulok	Phetchabun		Overall mean
	Dry season	Rainy season	Dry season	Rainy season	Rainy season	Dry season	
CN84-1	194.64 bc[1/]	249.45 c	261.78	346.71	339.54	271.34	279.95 d
P08	209.94 bc	290.19 bc	294.45	338.45	321.71	337.88	298.77 bcd
P12	250.84 a	321.53 b	327.34	330.22	318.69	315.78	310.73 bc
P22	234.00 ab	399.60 a	329.29	420.84	388.79	312.95	347.58 a
P24	209.15 bc	312.78 bc	305.87	415.90	368.67	325.72	323.02 ab
CN3	193.44 c	275.06 bc	293.33	315.34	293.92	298.63	278.29 d
SUT1	207.68 bc	278.79 bc	298.44	356.56	295.83	282.77	286.68 cd
Mean	214.24	306.64	303.48	360.57	332.45	306.44	303.95
F-test	*[2/]	*	ns	ns	ns	ns	**
Genotypes (G)			**				
Locations (L)			**				
Seasons (S)			ns				
G x L			ns				
G x S			ns				
G x L x S			ns				
C.V. (%)			13.01				

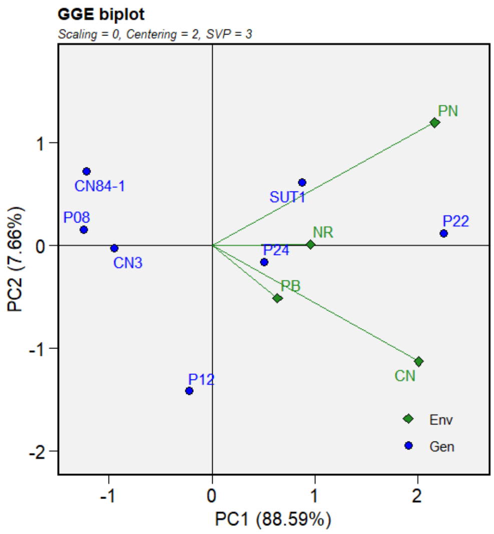
[1/] Data showing means, different letters in column indicate statistically significant differences at 95% confidence level by comparing means using Duncan's New Multiple Range Test (DMRT). [2/] ns = not significant, * = significant at $P \leq 0.05$; ** = highly significant at $P \leq 0.01$, and ns=non-significant at $P > 0.05$.

3.4.10 Evaluation of GEI using symmetrical GGE biplot analysis

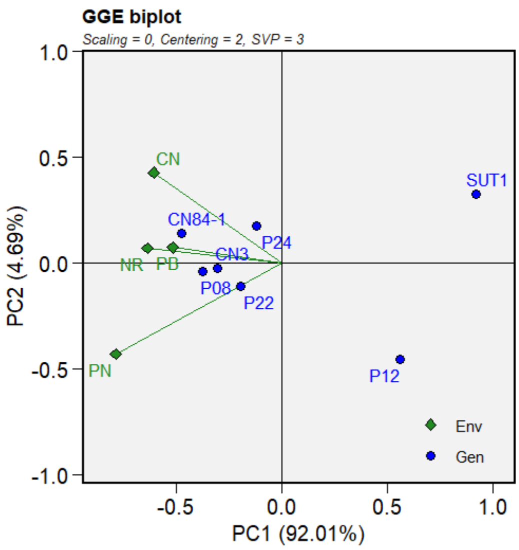
The yield potential and stability of all mungbean genotypes, including CN84-1, P08, P12, P22, P24, CN3, and SUT1, were evaluated across four locations: Nakhon Ratchasima, Chai Nat, Phitsanulok, and Phetchabun. Agronomic traits, including pods/plant, 100 seed weight, and yield, were assessed and displayed in Patterns A, B, and C, respectively.

A symmetrical GGE biplot analysis was conducted to evaluate the relationships among the test environments and to determine the proportion of variance attributable to the GEI, as explained by principal components (PC) 1 and PC2. The results revealed that the cumulative variances of PC1 and PC2 accounted for 96.25% of the GEI for pods/plant, 96.7% for 100 seed weight, and 95.05% for yield. Based on the symmetrical GGE biplot, the relationship between test environments was assessed using environmental vectors, which are lines drawn away from the biplot origin at x,y = 0.0,0.0 to each environment as shown with green lines in Figure 3.3. Environments forming acute angles between their vectors were positively correlated, whereas obtuse angles indicated negative correlations. Right angles suggested no correlation between environments. In addition, the distance between two environments reflected their ability to discriminate among the mungbean genotypes. For pods/plant (Figure 3.3, Pattern A), Chai Nat and Phetchabun exhibited a positive correlation, providing the most consistent genotype data across both locations. For 100 seed weight and yield (Figure 3.3, Pattern B and C), Nakhon Ratchasima and Phetchabun were positively correlated, indicating the most consistent genotype responses in these environments for both traits.

Pattern A: Pods/plant



Pattern B: 100 seed



Pattern C: Yield

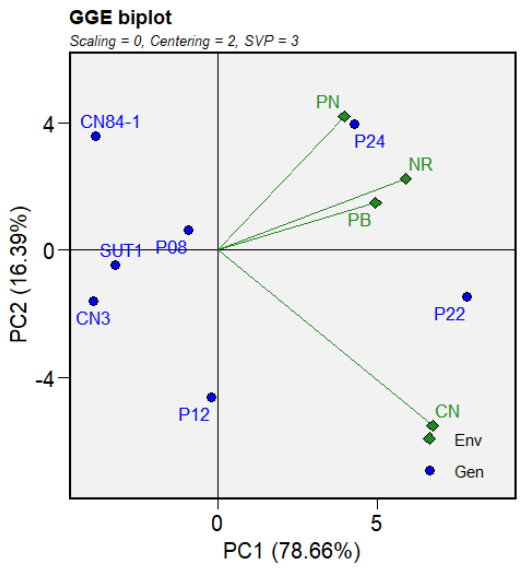


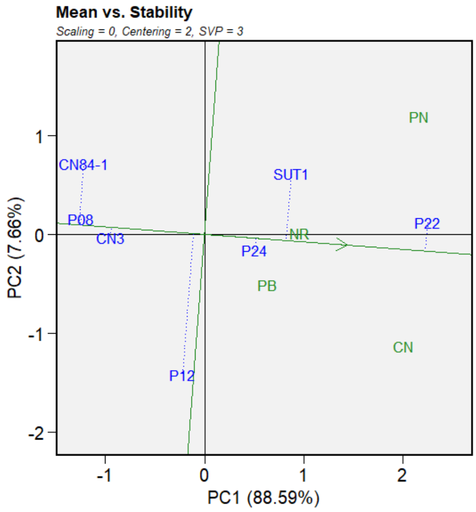
Figure 3.3 The GGE biplot 'Symmetrical' pattern illustrating the effects of the first two principal components (PC1 and PC2) of seven mungbean genotypes evaluated across four locations and two seasons. Abbreviation: NR = Nakhon Ratchasima, CN = Chai Nat, PN = Phitsanulok, and PB = Phetchabun.

3.4.11 Evaluation of genotypes based on mean performance and stability

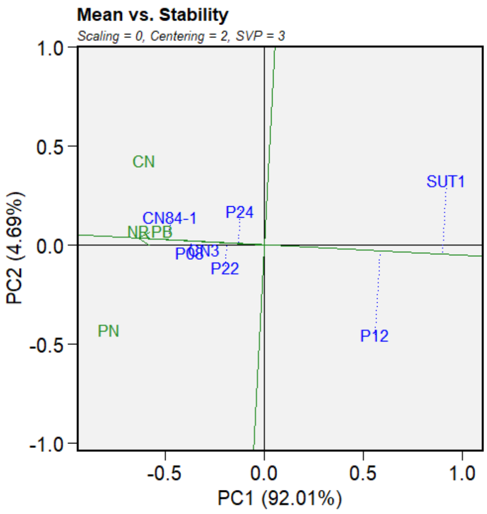
A stability analysis of mungbean genotypes across four test locations was performed utilizing the GGE biplot approach under the 'Mean vs. Stability' perspective (Figure 3.4). The biplot displays the ranking of genotypes according to their overall performance across various locations, utilizing the AEC to visually represent both mean performance and stability. This examination demonstrates the performance and stability of each genotype. The stability of the genotype and GEI are represented by a green line. The vertical axis is called the 'AEC ordinate,' while the horizontal axis is the 'AEC abscissa.' The length of the genotype's projection along this line indicates its stability longer projections signify lower stability.

For pods/plant (Figure 3.4, Pattern A), line P22 exhibited the highest performance compared to other genotypes, followed by SUT1, P24, and P12, respectively. In contrast, line P08 and CN84-1 had the lowest pods/plant. However, line P08 was closest to the AEC abscissa, indicating the highest stability among all genotypes. Since the AEC ordinate reflects the degree of instability, the low projection of P08 onto this axis further confirmed its stable performance across environments. Additionally, P22 and P24 showed relatively high pods/plant with good stability as well. In the analysis of 100 seed weight (Figure 3.4, Pattern B), the AEC abscissa extended in the negative direction to the left side, indicating that the recurrent parent CN84-1 had the highest 100 seed weight, followed by lines P08, CN3, P22, P24, and P12, respectively. Although line P08 had slightly lower seed weight than CN84-1, but it exhibited greater stability, as reflected by its proximity to the AEC abscissa and minimal projection onto the AEC ordinate. Both P08 and CN3 were classified as genotypes with large seeds and high stability. For the performance and stability of yield as shown in (Figure 3.4, Pattern C), line P22 achieved the highest average yield, followed by P24, P12, and P08. Variety CN3 had the lowest yield among all genotypes. Notably, line P22 combined high yield and stability. Although line P08 exhibited moderate yield performance, it exhibited the highest level of stability among the new mungbean lines, as indicated by its close alignment with the AEC abscissa and low value on the AEC ordinate.

Pattern A: Pods/plant



Pattern B: 100 seed weight



Pattern C: Yield

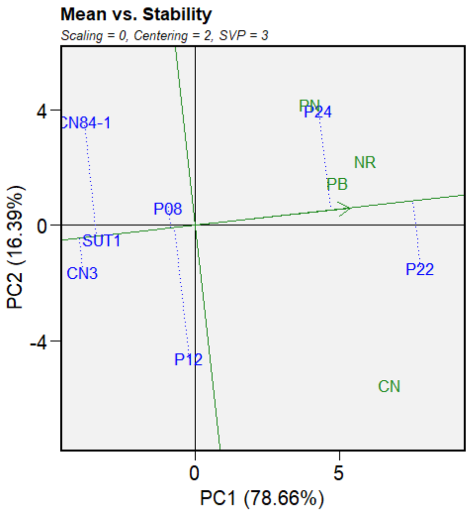


Figure 3.4 The GGE biplot 'Mean vs. stability' pattern illustrating interaction effect of seven mungbean genotypes evaluated across four locations and two seasons. Abbreviation: NR = Nakhon Ratchasima, CN = Chai Nat, PN = Phitsanulok, and PB = Phetchabun.

3.4.12 Identification of mega environments and 'Which-won-where'

The suitability of mungbean genotypes across environments was assessed using the GGE biplot represented as a polygon showing 'Which-won-where' pattern. Vertical lines, the so-called "equality lines," are then subsequently drawn from the origin (0.0,0.0) to different sides of polygon to divide it into sectors called "mega environment". This graph helps to pinpoint major environments and genotypes with specialized resilience. The G+G×E variation accounted for 96.25%, 96.70%, and 95.05% for pods/plant, 100 seed weight, and yield, respectively (Figure 3.5).

For pods/plant, the polygon was divided into only a single sector, as all test locations were grouped within the same boundary. Line P22 demonstrated the highest pods/plant performance across all locations, followed by variety SUT1 (Figure 3.5, Pattern A). Regarding 100 seed weight, only one sector was also identified. The recurrent parent CN84-1 exhibited the highest 100 seed weight performance across locations, followed by line P08 (Figure 3.5, Pattern B). In contrast, for yield (Figure 3.4, Pattern C), the test environments were grouped into two distinct sectors representing 2 mega environments. The first group included Phitsanulok, while the second group comprised Nakhon Ratchasima, Phetchabun, and Chai Nat. The result found that line P22 showed the highest yield and was the best adapted to the second group of locations, followed by P24 and P24 was best suited for cultivation in the first group.

Considering genotype-specific adaptation to environments, observation based on the proximity of close genotype and environment points on the biplot graph. The result indicated that pods/plant of P22 was particularly well-suited adaptation to Phitsanulok and Chai Nat, while variety SUT1 was best to Nakhon Ratchasima (Figure 3.5, Pattern A). For 100- seeds weight, CN84-1 was the most suitable adaptation for Phetchabun, followed by Nakhon Ratchasima and Chai Nat, respectively, whereas line P08 was particularly adapted to Phetchabun and Nakhon Ratchasima as shown in (Figure 3.5, Pattern B). Regarding yield, the high yield production and suitable adaptation of line P24 was best at Phitsanulok followed by Nakhon Ratchasima and Phetchabun, respectively. Whereas line P22 showed better adaptation to Nakhon Ratchasima, Phetchabun, and Chai Nat (Figure 3.5, Pattern C).

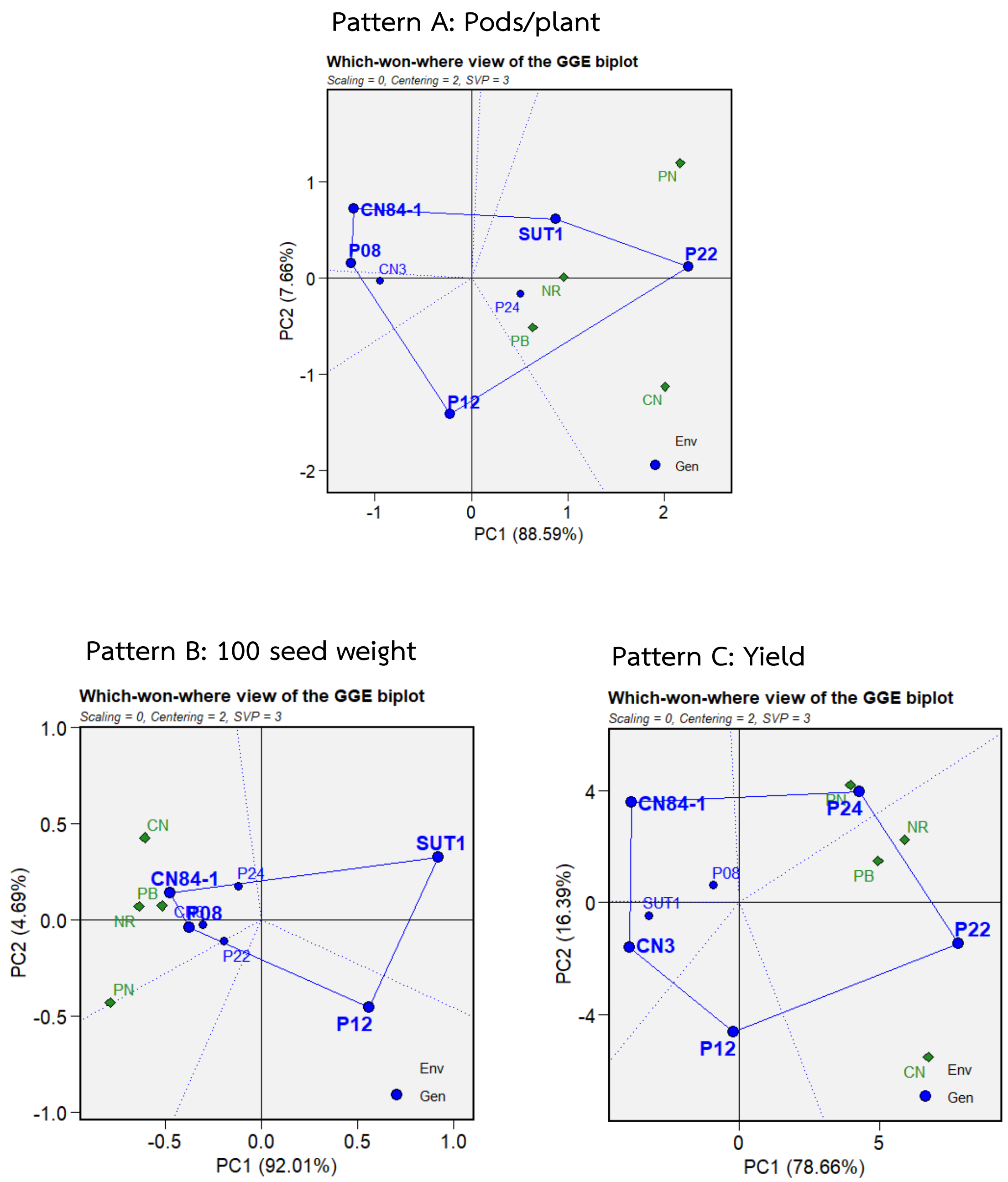


Figure 3.5 The polygon GGE biplot 'Which-won-where' view displaying the genotype main effect plus G×E interaction effect of seven mungbean genotypes evaluated across four locations and two seasons. Abbreviation: NR = Nakhon Ratchasima, CN = Chai Nat, PN = Phitsanulok, and PB = Phetchabun.

3.4.13 Assessment of testing locations: discriminative vs. representativeness and desirability index

The evaluation potential of each environment for distinguishing the mungbean genotypes, GGE biplot analysis under the Discrimitiveness (the ability of an environment to distinguish genotype) vs representativeness (the ability of an environment to represent all other evaluated environments) pattern was performed (Figure 3.6). The analysis used the AEC, illustrated by a green arrow originating from the biplot center point (0.0,0.0), which represents the average variance of PC1 and PC2 across all tested environments. In the GGE biplot approach, three variables are crucial for evaluating test locations: discrimination power, representativeness, and desirability index. The "discriminating ability" specified by extent of the environmental vector that corresponds to standard deviation within experimental location. Environments vectors with longer vectors are more effective at discriminating against the different genotypes classified as "discriminating locations" due to their ability to differentiate between genotypes. The representativeness of experimental sites is driven by acute angles formed by environment vectors and the AEC abscissa. The acute angles with the AEC abscissa, identifying as "most representative" experimental locations. The desirability index of experimental sites combines both its discriminative ability and representativeness.

For the discriminative environment indicated that Phitsanulok was the most discriminative environment for pods/plant and 100 seed weight, while Chai Nat was the most discriminative environment for yield (Figure 3.6, Pattern A, B, and C). Regarding the representativeness of each location, which can be assessed by the angle relative to AEC abscissa, it was found that for pods/plant and 100 seed weight, the Nakhon Ratchasima location served as the most representative environment. In contrast, for yield, the Phetchabun location was identified as the most representative and provided a highly stable testing environment for yield evaluation (Figure 3.6, Pattern C). The desirability index indicated that Nakhon Ratchasima had the highest desirability for 100 seed weight and yield, while Chai Nat showed the highest desirability for pod/plant. These locations exhibited long environmental vectors and formed acute angles with the AEC abscissa.

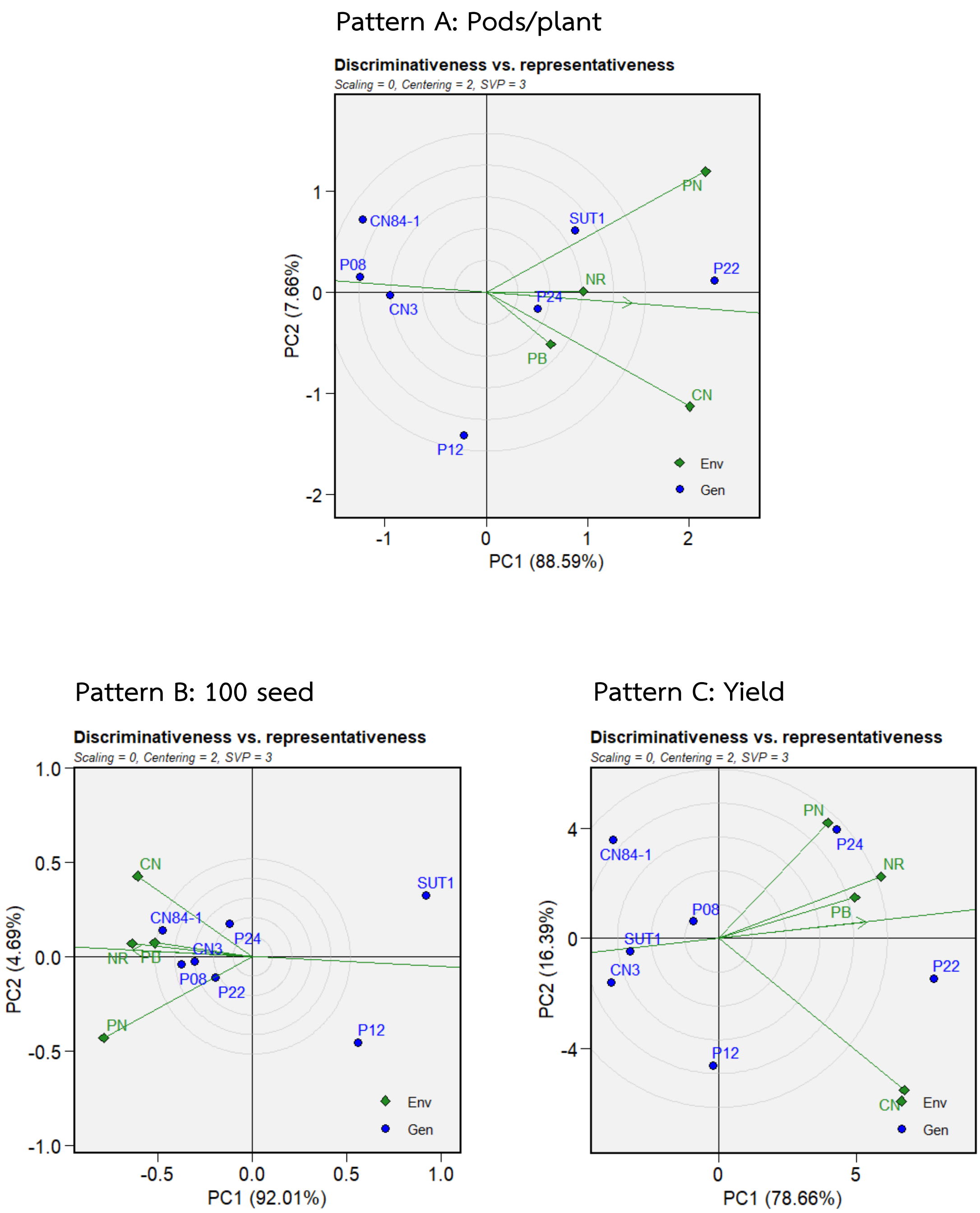


Figure 3.6 The GGE biplot 'Discriminativeness vs. Representativeness' pattern for genotype comparison with ideal genotype showing G+G×E interaction effects of seven mungbean genotypes evaluated across four locations and two seasons. Abbreviation: NR = Nakhon Ratchasima, CN = Chai Nat, PN = Phitsanulok, and PB = Phetchabun.

3.5 Discussion

The regional yield trial of eight mungbean genotypes CN84-1 (recurrent parent), SUPER5 (resistant line), two check varieties (CN3 and SUT1), and four new mungbean lines (P08, P12, P22, and P24) was conducted. The four new lines were derived from BC_4F_{10} generation plants developed through a backcrossing method. The donor parent was obtained from an F_3 generation of a double cross between genotypes CN72, V4718, V4758, and V4785, subsequently backcrossed to the recurrent parent CN84-1, which possessed high yield but was susceptible to diseases, for breeding new varieties introducing resistance to both CLS and PM. The double cross was derived from [(CN72 × V4758) × (CN72 × V4718)] × [(CN72 × V4718) × (CN72 × V4785)] (Pookhamsak et al., unpublished data). The donor parent lines V4718, V4758, and V4785 were resistant lines sourced from India (Nair & Schreinemachers, 2020). All three donor lines have been reported to carry resistance to PM (Chueakhunthod et al., 2020). Additionally, V4718 has a single dominant gene conferring resistance to CLS (Chankaew et al., 2011; Tantasawat et al., 2020). CLS and PM are the major diseases affecting mungbean production. CLS, caused by *Cercospora canescens*, can reduce mungbean yield by up to 50% if infection occurs after the flowering stage (Asian Vegetable Research and Development Center, 1974, 1975). PM, caused by *Sphaerotheca phaseoli*, can result in yield losses of up to 40% if disease management practices are not implemented (Tsou et al., 1979). The Indian donor lines V4718, V4758, and V4785 possess resistance genes that effectively counter these diseases.

Following the development and preliminary evaluation of these resistant lines, previously the superior lines P08, P12, P22, and P24 were selected through standard trials and subsequently included in this regional trial (multi-environment trials). This study involved the evaluation of key agronomic traits, disease resistance (CLS and PM), stability and performance of the new mungbean lines. Regional yield trials were conducted at four locations (Nakhon Ratchasima, Chai Nat, Phitsanulok, and Phetchabun) across two seasons (rainy and dry seasons) during the years 2023-2024.

3.5.1 Performance of new mungbean lines across environments

3.5.1.1 Line P08

During the rainy season, P08 exhibited agronomic traits that were mostly lower than or comparable to the recurrent parent CN84-1 across all environments. The yield had tended to be lower among new mungbean lines, except for P12. Line P08 demonstrated moderate resistance to PM and CLS in all environments except at Phetchabun. In the dry season trials at Nakhon Ratchasima and Chai Nat, P08 tended to produce lower yields than P12, P22, and P24 but outperformed the recurrent parent at both sites. Its level of PM resistance varied according to disease outbreak, ranging from susceptible (Chai Nat) to resistant (Phitsanulok), and was comparable to the recurrent parent and check varieties. Agronomic traits of P08 during the dry season were generally better than during the rainy season across all locations.

3.5.1.2 Line P12

During the rainy season, line P12 exhibited characteristics that generally tended to be lower than those of the recurrent parent CN84-1, particularly in seed weight/plant and yield across all environments, except at Chai Nat. Line P12 also exhibited longer days to flowering, days to maturity, and greater plant height, which contributed to an increased risk of lodging during the rainy season. However, results of the dry season showed non-significant differences in plant height among genotypes, although P12 still exhibited higher lodging rates than other genotypes. Additionally, P12 matured later than the other genotypes. Line P12 showed moderate resistance to PM and high resistance to CLS across all environments. In the dry season, the agronomic traits of P12 tended to perform better than the recurrent parent, except at Phitsanulok, where it recorded the lowest values among all tested genotypes, however, the differences were not statistically significant. Conversely, at Nakhon Ratchasima, P12 exhibited the highest yield, outperforming all check varieties and recurrent parent, followed by its performance at Chai Nat. Resistance to PM was consistent with that of P08, with P12 demonstrating better resistance than the recurrent parent. Overall, P12 showed better adaptation and stronger disease resistance during the dry season compared to the rainy season across all environments, with particularly outstanding performance observed at Nakhon Ratchasima during the dry season.

3.5.1.3 Line P22

During the rainy season, P22 consistently exhibited agronomic traits superior to those of the recurrent parent CN84-1 and outperformed P08, P12, and P24 across all environments. P22 demonstrated moderate resistance to PM and moderate to high resistance to CLS. In the dry season, P22 showed higher yields than all check varieties and recurrent parent across all environments, with the highest yield recorded at Chai Nat, followed by Nakhon Ratchasima and Phitsanulok. Although yield tended to be lower in the dry season compared to the rainy season, P22 maintained better PM resistance than the recurrent parent, especially at Chai Nat, where it was high in disease outbreak. Despite the severe PM outbreak at Chai Nat, P22 still achieved the highest yield among all tested genotypes. This highlights P22 strong adaptability and disease resilience, contributing to its superior yield stability, particularly at Chai Nat across both seasons.

3.5.1.4 Line P24

During the rainy season, P24 exhibited agronomic traits superior to those of the recurrent parent CN84-1 across almost all traits and environments, with particularly outstanding performance at Nakhon Ratchasima. However, its yield was generally lower than or comparable to P22. P24 demonstrated moderate resistance to PM and good resistance to CLS across all environments. In the dry season, P24 consistently outperformed both the recurrent parent and check varieties in all environments, achieving the highest yields particularly at Phitsanulok and Phetchabun. Disease evaluations revealed that P24 generally had the lowest disease scores among the new mungbean lines. Overall, line P24 demonstrated superior performance compared to the recurrent parent and check varieties across both seasons and showed excellent adaptability, maintaining high yield performance in several environments.

3.5.2 The combined variance analysis of yield

The combined variance analysis of yield was conducted to determine whether environmental factors or seasonal variation significantly influenced mungbean yield. The analysis highlighted significant effects of G and L on yield performance, whereas the effects of S, G × L, G × S, and G × L × S interactions were not significant. These findings suggest that genotypic differences and specific location factors were the primary determinants of yield variation, consistent with patterns previously reported in legume crops, including mungbean (Kang, 1997; Yan et al., 2007). Among the agronomic traits evaluated in this study, yield was identified as the most critical trait of interest to farmers. Based on the combined variance analysis across the environments where data combination was possible, line P22 consistently exhibited superior yield performance, followed by line P24. In contrast, the recurrent parent CN84-1 consistently recorded the lowest average yield among all tested genotypes, with the differences being statistically significant.

3.5.3 Stability analysis from GGE biplots approaches

Multi-environment stability analysis using GGE biplots provided additional insights into the performance consistency of the mungbean genotypes across diverse environments. Assessing various genotypes in different locations presents a considerable challenge. Therefore, selecting appropriate test locations is crucial for conducting efficient and cost-effective multi-environment trials (Parihar et al., 2017; Munaro et al., 2020). The GGE biplot approach provides an effective solution to these challenges by enabling the evaluation of genotypes and identifying the best experimental locations, which can be categorized into distinct mega-environments, irrespective of their agroecological zones (Naık et al., 2022). The significant presence of Genotypes and Locations in combined analysis of yield association underscores the necessity of multilocation evaluation of genotypes (Irfan et al., 2025).

The ‘symmetrical’ GGE biplot was conducted to examine the relationship between genotypes and environments based on pods/plant, 100 seed weight, and yield. For pods/plant, Chai Nat and Phetchabun exhibited a positive correlation, providing the most consistent genotype data across both locations. For 100 seed weight and yield, Nakhon Ratchasima and Phetchabun were positively correlated, indicating the most consistent genotype responses in these environments for both traits.

In GGE biplot view ‘Mean vs. Stability’ the AEC abscissa denotes elevated average performance, while the AEC ordinate indicates genotype stability and depicts the contribution of genotype to GEI (Yan et al., 2007; Pour-Aboughadareh et al., 2023; Basnet, 2024; Kunwar et al., 2024; Irfan et al., 2025). The result revealed that line P22 combined high performance and stable yield across environments, while P08, despite moderate yield, demonstrated the highest stability. P24 showed relatively high pods/plant with well stability. Whereas CN84-1 had the highest 100 seed weight, followed by lines P08 and CN3 respectively. Both P08 and CN3 were classified as genotypes with large seeds and high stability. Line P22 achieved the highest average yield and stability, followed by P24, P12, and P08. Variety CN3 had the lowest yield among all genotypes. The combination of performance and stability is essential for the recommendation of new cultivars for wide-scale cultivation (Yan & Tinker, 2006)

The GGE biplot 'Which-won-where' analysis demonstrated environment-specific advantages of genotypes. According to the GGE biplot analysis, an ideal experimental location should be identified based on its ability to designate genotypes, represent the mega-environment, and have a high desirability index (Yan et al., 2007; Badu-Apraku et al., 2020; Mohammadi et al., 2023; Basnet, 2024). For pods/plant, Line P22 demonstrated the highest pods/plant performance across all locations, followed by variety SUT1, while for 100 seed weight, CN84-1 retained superiority. Line P22 performed best for yield in environments such as Nakhon Ratchasima, Chai Nat, and Phetchabun, whereas P24 showed superior adaptation to Phitsanulok. These observations emphasize the importance of multi-trait selection across environments to maximize genetic gains in mungbean breeding (Yan et al., 2007).

Furthermore, the ‘Discriminativeness vs. Representativeness’ visualization enabling the elimination of unnecessary testing locations while preserving trial heritability and genetic gain, thus enhancing the selection process in a cost-effective way (Yan et al., 2007; Badu-Apraku et al., 2020). The GGE biplot analysis showed that Phitsanulok was the most discriminative environment for pods/plant and 100 seed weight, whereas Chai Nat was the best for discriminating against yield differences. For representative environment, Nakhon Ratchasima was ideal for pods/plant and 100 seed weight evaluations, while Phetchabun was identified as the most representative environment for yield testing. The desirability index indicated that the maximum desirability index for pods/plant, 100 seed weight, and yield were observed at Chai Nat, Nakhon Ratchasima, and Nakhon Ratchasima, respectively. Resulting from long environmental vectors and formed acute angles with the AEC abscissa. Such analyses highlight the critical role of selecting optimal testing environments to ensure effective genotype differentiation and reliable selection decisions (Yan et al., 2007).

3.6 Conclusion

The evaluation of new mungbean lines across multiple environments and seasons. Among the tested lines, P22 and P24 consistently exhibited superior yield performance across various environments. Line P22 achieved the highest overall yield, with strong adaptability and stability, particularly in environments with high disease outbreak. P24 also demonstrated excellent yield potential, especially at Phitsanulok and Phetchabun, indicating its broad adaptability across both favorable and moderately stressed conditions. Both lines exhibited synchronous pod maturity. Line P12, showing resistance to CLS and moderate resistance to PM, presented delayed flowering, maturity, and high lodging under rainy season. However, in the dry season, P12 was achieving the highest yield at Nakhon Ratchasima. These results suggest that P12 is better suited for dry season cultivation. Line P08 exhibited agronomic performance comparable or lower than recurrent parent. Although its yield was lower than that of P22 and P24. Line P08 maintained better performance than CN84-1 under dry season and exhibited high yield stability across environments. The ‘symmetrical’ GGE biplots resulted that Chai Nat and Phetchabun were positively correlated for pods/plant, while Nakhon Ratchasima and Phetchabun responses for 100 seed weight and yield. Line P22 demonstrated high yield and moderate stability, while P08 showed the highest stability in yield. The GGE biplot ‘Mean vs. Stability’ analysis revealed that line P22 exhibited the highest performance and stability in pods/plant and yield. P08 demonstrated the highest stability for pods/plant and 100 seed weight. Line P24 exhibited well performance with high stability, while CN3 showed the lowest yield.

The 'Which-won-where' analysis revealed significant GEI, with line P22 showing the best performance for pods/plant and yield, particularly in Phitsanulok and Chai Nat. CN84-1 and P08 were the top performers for 100 seed weight. Line P24 was best at Phitsanulok whereas line P22 showed better adaptation to Phetchabun and Chai Nat. The GGE biplot analysis 'Discriminative vs. Representativeness', resulting that Chai Nat was the most discriminative for yield. Phetchabun was the most representative for yield. The desirability index indicated that Nakhon Ratchasima had the highest desirability for 100 seed weight and yield, while Chai Nat showed the highest desirability for pods/plant.

3.7 References

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