

Article

Identification of Superior Soybean Cultivars through the Indication of Specific Adaptabilities within Duo-Environments for Year-Round Soybean Production in Northeast Thailand

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Abstract: The soybean (*Glycine max* (L.) Merrill) is one of the world's most important sources of food, feed, and fuel due to its high protein value and oil content. However, there exists a lack of soybean genotypes suitable for growth in diverse conditions as soybean breeders have developed their own varieties for specific purposes within their own unique environments. This, therefore, creates the need for soybean genotypes for different environments. The objectives of the experiment described herein were to determine the genotype magnitude through the environment interaction (G×E) of new soybean breeding lines, thereby identifying widely and/or specifically adapted genotypes under ten of Northeast Thailand's typical environmental conditions from 2017 to 2019. Analyses of the environment (E) and G×E captured a large portion of the total sum of squares of grain yield and related traits, which demonstrated the influence of the two factors in evaluating soybean genotypes, thereby identifying the need for response analysis to identify superior genotypes in each environment. Based on the grain yields of three environments, four genotype groups were clustered. Within the high grain yield environment (EG1), we identified five genotypes with higher yield performance (35*sj-32 (3356 kg/ha), 38D*a-16 (3138 kg/ha), 42*Ly-50-2 (3122 kg/ha), 35*Lh-7 (3116 kg/ha), and 223*Lh-85 (3073 kg/ha)) of KK (3132 kg/ha), the recommended soybean variety for Northeast Thailand, than that of the CM60 (2606 kg/ha). These five top-yielding genotypes, however, produced unstable grain yields through varied environments as they were each narrowly adapted to a specific environment. Moreover, those genotypes may be grown within a rotational cropping system in a duo-environment (wet and dry season) of soybean production in Thailand's northeast region.

Keywords: CM60; lowland paddy fields; breeding lines; crop rotation; dry season



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1. Introduction

Soybean (*Glycine max* L. Merrill) is one of the most important grain crops for both humans and livestock, representing a staple source of nutritious vegetable proteins and oil, as well as viable industrial materials and biofuel. The diverse geographic distribution of wild soybean species throughout China indicates that China was the diversification center of the cultivated soybean [1], which gradually spread to Korea, Japan, India, Thailand, Indonesia, the Philippines, and other Asian countries over time [2–4]. As a result of such widespread distribution, a great number of soybean varieties were selected to grow under different environmental conditions that included soil characteristics, temperature, photoperiod, and rainfall.

Each area's environmental conditions were also paired with the varied processing techniques developed by individual farmers [1], thereby leading to difficulties in identifying superior, stable cultivars for each region. Therefore, a single cultivar may perform

differently according to the environment influenced by the presence of a significant genotype and environment interaction (G×E) [5–8]. In large-scale soybean production, seed production is a critical factor that will either limit or broaden the production area, thereby necessitating the identification and selection of soybean genotypes with greater adaptability and yield stability, together with diminished effects of a G×E interaction. Studies conducted worldwide [4,9–13] have stressed the necessity to develop environmentally adapted soybean genotypes.

In Thailand, soybeans are thought to have been introduced through Chinese migration in the 18th century. Thailand's Department of Agriculture (DOA) created its soybean breeding program in 1960, which released 15 soybean cultivars throughout the country: SJ1, SJ2, SJ3, SJ4, SJ5, SukhoThai1, SukhoThai2, SukhoThai3, Srisamrong1, NS1, CM1, CM2, CM3, CM4, and CM60. Among these cultivars, SJ5 and CM60 have become the most widely accepted among farmers due to their productivity, adaptability, and consumption attributes [9], which are useful in creating several soy products, such as soymilk and tofu. For example, CM60 produces high protein content (36%) and a less "beany" taste most suitable for making soy milk. The predominance of these two soybean cultivars has led to few literary studies aimed at the development of other soybean cultivars, specifically, those addressing regions with dissimilar environmental conditions.

Thailand's major area of soybean production lies in the northern region, followed by the northeast and central regions. In past years, soybean cropping systems across Thailand involved the alternate transfer of soybean seeds in the rainy season in upland areas of the north and the dry season in the lowland paddy fields of the central and northeast regions. Today, such cropping systems have changed due to several factors, such as (1) government policies that required a decrease in the crop production in mountainous areas; (2) lower profits of soybean production compared with other crops; (3) the substitution of other crops, such as vegetables in the lowland paddy fields of the central and northeast regions; (4) climate change, which adversely affects the cropping schedule in varied regions, as well as failed seed production; and (5) the aging society of soybean growers and the lack of advanced mechanized technology in soybean production. As a result, Thailand's total soybean production area dramatically declined over the last two decades from 0.30 M ha in 2000 to 0.03 M ha in 2020 [14].

Based on the fluctuation of rainfall and the water status in major dams, the Thai DOA has requested that the second rice production in the lowland paddy fields of the central region during the dry season be replaced with less water-dependent crops, such as soybean and vegetables. However, soybean production is limited by the lack of specific adaptability to varied environments [15] and the low quality of yield and product that does not meet consumer, nutrition, and manufacturer preferences of the above-mentioned 15 soybean cultivars. Therefore, the evaluation of new soybean breeding lines with commercial soybean cultivars is needed to produce environmentally adaptable cultivars. The objective of this study, therefore, was to evaluate the yield potential of soybean cultivars and their stability and adaptability throughout the soybean production areas of Northeast Thailand.

2. Materials and Methods

2.1. Plant Material and Experimental Design

Twenty-four soybean genotypes comprising 6 commercial and 18 breeding lines derived from several crosses by pedigree selection since 2004 (Table 1) were grown in 10 environmentally contrasting locations. The environmental conditions were separated based on the different planting locations that cover three growing commercial soybean production areas in the northeastern part of Thailand. In each environment, there were differences in planting time, rainy day, soil type, and growing method that depended on the farmer's practice. At each location, we employed a randomized complete-block design with three replications. The experimental units consisted of four parallel 4 m long rows per genotype spaced 25 cm between plants and 50 cm between rows, with 17 plants per row. Sowing took place from June to August for the wet season and from December to

January for the dry season according to local practices. At 15 days after planting (DAP), plants were thinned to three plants per hole, and weeds were controlled by hand weeding. Fertilizer was initially applied at the rate of 14.06 kg/ha (N₂-P₂O₅-K₂O). At 30 DAP, a second fertilizer application was applied at the rate of 18.75 kgN₂/ha, 37.50 kgP₂O₅/ha, and 18.75 kgK₂O/ha. Herbicides and insecticides were used as necessary, as recommended by Thailand's DOA, and irrigation was practiced throughout the dry season as required.

Table 1. Variety type and source of soybean genotypes used in all experiments.

Genotype	Variety Type	Cross	Maturity Type	Source
44*Ly-4E	Breeding line	(KKU35 × Horei) × Lyon	Intermediate	Khon Kaen University
44*Ly-14E	Breeding line	(KKU35 × Horei) × Lyon	Intermediate	Khon Kaen University
40*Ly-15	Breeding line	(KKU35 × Horei) × Lyon	Intermediate	Khon Kaen University
42*Ly-50-2	Breeding line	(KKU35 × Horei) × Lyon	Intermediate	Khon Kaen University
44*Ly-6-1-2-7	Breeding line	(KKU35 × Horei) × Lyon	Intermediate	Khon Kaen University
44*Lh-4	Breeding line	(KKU35 × Horei) × UFV 80-85	Intermediate	Khon Kaen University
38D*a-16	Breeding line	KKU35 × NS1	Intermediate	Khon Kaen University
KKU74	Breeding line	NS1 × KKU35	Intermediate	Khon Kaen University
KKU5e	Breeding line	NS1 × KKU35	Intermediate	Khon Kaen University
74-T4	Breeding line	NS1 × KKU35	Intermediate	Khon Kaen University
223*Lh-85	Breeding line	(NS1 × KKU35) × UFV 80-85	Intermediate	Khon Kaen University
76*B-14-1-3	Breeding line	NS1 × KKU35	Intermediate	Khon Kaen University
35*M-4	Breeding line	SJ2 × Williams	Intermediate	Khon Kaen University
35*Lh-7	Breeding line	SJ2 × Williams	Intermediate	Khon Kaen University
35*sj-32	Breeding line	SJ2 × Williams	Intermediate	Khon Kaen University
44*Lh-96	Breeding line	(KKU35 × Horei) × UFV 80-85	Intermediate	Khon Kaen University
42*Lh-1-1-1	Breeding line	(KKU35 × Horei) × UFV 80-85	Intermediate	Khon Kaen University
KKU35*m-7-2	Breeding line	SJ2 × Williams	Intermediate	Khon Kaen University
CM60	Check variety	-	Intermediate	DOA, Thailand
SJ5	Check variety	-	Intermediate	DOA, Thailand
KK	Check variety	-	Intermediate	DOA, Thailand
CM6	Check variety	-	Intermediate	DOA, Thailand
NS1	Check variety	-	Early	DOA, Thailand
KKU35	Check variety	-	Late	Khon Kaen University

2.2. Data Collection

The amount of rainfall was recorded at each site by a weather station close to the experiment site (<2 km). Days to flowering (DTF) was estimated in each environment by recording the date in which 50% of the plants in each plot showed at least one fully bloomed flower. Grain yields were recorded in four random plants from the middle row in each plot and then weighed. Plant height, also measured in four random plants from the middle row, determined the distance from the soil surface to the top of the plant. The number of nodes and pods were counted from four random plants, and the pod heights of 10 random plants were measured from the soil surface to the node of the first pod. One hundred viable seeds were weighed. Harvesting took place from late October to early November in the wet season, and from late March to mid-April in the dry season, depending on their respective environmental conditions.

2.3. Statistical Analysis

A combined ANOVA for randomized complete-block design through each environment was carried out via R-Stat [16] for each trait. For all 10 environments, the 24 genotypes were combined, and the sum square percentage was calculated based on the mean square of environment (E), genotype (G), and environment by genotype interaction (G×E). Multiple comparisons were analyzed by Duncan's Multiple Range Test (DMRT) using the Statistical Tool for Agricultural Research (STAR) software (<http://bbi.irri.org/products>, accessed on 30 December 2020). A group analysis obtained through Ward's hierarchical clustering method generated a dendrogram, which was used to determine prior information

involving the number of groups [17]. Clustering was performed for both the genotype and environmental groups based on the established between-group linkage distances. The dissimilarity measurement between genotypes was based on the Euclidian distance. These analyses were designed to improve the discrimination of superior genotypes and were used to compare the results from each environmental condition, as well as the stability of each genotype group. Cluster statistical analyses were performed using MEGA v.10 software [18].

3. Results

Ten contrasting location/year environments were evaluated, which included such factors as growing season, soil type, amount of rainfall, number of rainy days, and planting date (Table 2). These contrasting environments caused variations in grain yield, in which ENV1, ENV6, and ENV10 produced the highest grain yields (Table 2). Clustering based on grain yield resulted in the creation of three environmental groups: Group 1 (EG1) consisting of ENV1, ENV6, and ENV10; Group 2 (EG2) containing ENV3, ENV7, and ENV9; and Group 3 (EG3) made up of ENV2, ENV4, ENV5, and ENV8 (Figure 1). The groups were subsequently classified as having high (EG1), intermediate (EG2), and low (EG3) grain yields, which demonstrated the effects of different environmental conditions on the grain yields of various soybean genotypes.

Table 2. Description of the 10 environments of 24 soybean genotypes grown within the 2017–2019 cropping season in Northeast Thailand.

Environment	Growing Season	Soil Type	Rainfall (mm)	Rainy Days	Planting Date	Mean GY ^a (t/ha)
ENV1	Wet season	Loamy clay	525.0	56	3-Aug-2017	2733b
ENV2	Wet season	Loamy clay	436.2	40	9-Aug-2018	1106f
ENV3	Wet season	Loamy clay	403.9	28	23-Aug-2018	1682e
ENV4	Wet season	Sandy clay	716.0	79	22-Jun-2018	541g
ENV5	Dry season	Sandy	22.4	31	28-Dec-2017	1037f
ENV6	Dry season	Sandy clay	30.6	23	27-Dec-2017	2699c
ENV7	Dry season	Loamy clay	201.8	26	5-Jan-2018	1892de
ENV8	Dry season	Sandy	178.6	15	8-Dec-2018	985f
ENV9	Dry season	Sandy clay	541.8	37	12-Jan-2019	2013d
ENV10	Dry season	Loamy clay	447.6	39	4-Jan-2019	2983a

^a The different letter in the same column was significant at $p < 0.05$ by Duncan's multiple range test.

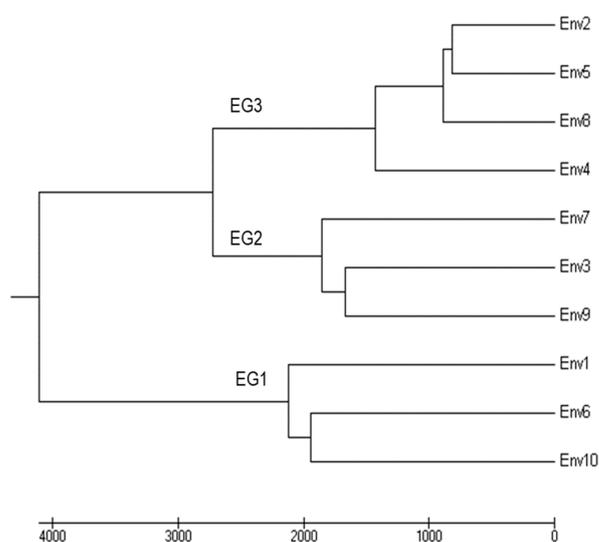


Figure 1. Environmental clustering based on grain yield through Ward's hierarchical clustering method.

The combined analyses of variance were calculated based on each trait from all 10 environments and 24 genotypes. The results showed for days to flowering (DTF), plant height, first-pod height, number of nodes, number of pods, seeds/pod, 100 seed weight, and grain yield (GY) of the 24 soybean genotypes under the 10 different environments that the principal effects (environment (E), genotype (G), and GxE interaction) were significant (Tables 3 and 4). These environmental factors accounted for more than 80% of the total sum of squares in all traits, except for the number of seeds/pod, in which only 31.64% was attributed to environmental effects (Table 4). The effects of seeds per pod were determined primarily from the genotypes. The results indicated that the environment had a major effect on GY, DTF, plant height, first-pod height, number of nodes, number of pods, and 100 seed weight of each soybean genotype.

Table 3. Combined analysis of variance for days to flowering (DTF), plant height, first-pod height, and the number of nodes of 24 soybean genotypes in 10 environments.

SOV	df	DTF ^a	%Respect SS	Plant Height ^a	% Respect SS	First Pod Height ^a	% Respect SS	Node Number ^a	% Respect SS
Environment (E)	9	2540.50 **	93.52	11,519.13 **	93.22	306.61 **	84.54	1937.25 **	79.53
Block/Env	2	29.45 **		255.03 **		34.47 **		35.51 **	
Genotypes (G)	23	155.79 **	5.73	749.09 **	6.06	44.37 **	12.23	455.99 **	18.72
GxE	207	20.20 **	0.75	89.24 **	0.72	11.72 **	3.23	42.76 **	1.75

^a Mean square value; ** significant at $p < 0.01$; % Respect SS included the effects of E + G + GxE.

Table 4. Combined analysis of variance for number of pods, seeds/pod, 100 seed weight, and grain yield (GY) of 24 soybean genotypes in 10 environments.

	df	Pod Number ^a	% Respect SS	Seed/Pod ^a	% Respect SS	100 Seed Weight ^a	% Respect SS	GY ^a	% Respect SS
Environment (E)	9	20,806.20 **	87.68	3.17 **	31.64	574.46 **	81.19	66,190,761 **	97.68
Block/Env	2	495.30 **		0.28 **		6.51 **		792,097 **	
Genotypes (G)	23	2542.20 **	10.71	6.78 **	67.66	126.25 **	17.84	949,552 **	1.40
GxE	207	381.60 **	1.61	0.07 *	0.70	6.86 **	0.97	622,823 **	0.92

^a Mean square value; * and ** significant at $p < 0.05$ and $p < 0.01$, respectively; % Respect SS included the effects of E + G + GxE.

Grain yield differences among genotypes were highly significant, in which the average grain yield ranged from 541 kg/ha (ENV4) to 2983 kg/ha (ENV10), while the mean grain yield across the 10 environments was 1767 kg/ha (Table 2). Three environmental group (EG) classifications based on grain yield are presented in Figure 1, and their respective mean grain yields of 24 genotypes in 10 locations are summarized in Table 5. The three soybean breeding lines K KU74, 223*Lh-85, and 35*sj-32 produced higher grain yields than those of the check cultivars CM60 and SJ5 (Table 5). Based on grain yield, the soybean genotypes were classified into four groups: Group 1 (GG1) comprising NS1; Group 2 (GG2) consisting of 44*Ly-6-1-2-7, 44*Lh-4, and K KU35*m-7-2; Group 3 (GG3) containing K KU5e, 74-T4, SJ5, and CM6; and Group 4 (GG4) made up of 44*Ly-4E, 44*Ly-14E, 40*Ly-15, 42*Ly-50-2, 38D*a-16, K KU74, 76*B-14-1-3, 35*M-4, 35*Lh-7, 35*sj-32, 44*Lh-96, 42*Lh-1-1, 223*Lh-85, CM60, K KU35, and K K (Figure 2 and Table 6).

Based on the responses of the genotype groups (GGs) within the different environmental groups (EGs), the lowest grain yields across all groups were obtained in GG1, whereas the highest grain yields were produced by GG4 across all groups. The results further indicated that the soybean genotypes in GG4 adapted particularly well to the EG1 (high yielding environment) (Figure 3, Table 6). Interestingly, the contrasting environments of the EG1 included both wet and dry seasons, loamy clay and sandy clay soil, and diverse amounts of rainfall (Table 2). The genotype group responses to each environmental group were also useful for genotype selection. Several breeding lines within GG4, including the common Thai variety CM60, produced higher yields than those of commercial varieties.

Table 5. Grain yields of 24 soybean genotypes in each environment (Env) under three environmental groups.

Genotype	Environmental Group 1			Environmental Group 2			Environmental Group 3				Genotype Mean
	Env1	Env6	Env10	Env3	Env9	Env7	Env2	Env4	Env5	Env8	
44*Ly-4E	2621	2848	3501	1650	1751	1611	1190	347	734	1140	1739
44*Ly-14E	2330	3214	2508	1601	2160	1571	1133	413	1156	933	1702
40*Ly-15	3493	3087	2562	2296	2158	2086	947	260	953	833	1867
42*Ly-50-2	2590	3411	3366	1342	1847	2322	907	620	1116	933	1845
44*Ly-6-1-2-7	2349	1918	3092	1712	2320	1130	830	461	1146	590	1555
44*Lh-4	1589	1711	3546	1992	2849	1388	962	818	757	740	1635
38D*a-16	2720	3533	3162	1318	1015	2037	1220	633	910	1581	1813
KKU74	2629	3203	3267	1213	2254	1784	1887	881	1240	1267	1962
KKU5e	3629	1572	2560	1665	2701	1893	1447	648	874	933	1792
74-T4	3450	2050	3002	1549	2047	1808	993	667	1665	1333	1856
223*Lh-85	2974	3074	3170	2050	3094	2092	1187	420	869	490	1942
76*B-14-1-3	2850	3047	3124	1457	1722	1799	920	333	843	840	1693
35*M-4	2859	3493	2767	1803	1805	1932	1707	501	1433	840	1914
35*Lh-7	1997	3984	3367	1433	1624	2733	833	360	742	1181	1825
35*sj-32	3280	3453	3335	1126	2127	2175	1202	480	988	1267	1943
CM60	2828	2699	2290	1475	2477	1458	1033	613	1276	900	1705
SJ5	3406	1970	2463	1381	1308	1881	960	708	676	667	1542
NS1	2065	1595	1220	2220	752	1319	1107	740	843	829	1269
KKU35	1960	2993	2770	1509	2204	2201	887	567	1323	1437	1785
KK	2999	3013	3385	2286	2034	1876	1020	473	990	840	1892
44*Lh-96	2718	2199	3662	2014	1569	3029	887	527	581	1300	1849
CM6	3309	1952	2600	1704	2352	1620	1373	687	1224	1140	1796
42*Lh-1-1-1	2656	2626	3174	1654	1771	2889	827	418	1244	645	1790
KKU35*m-7-2	2290	2137	3700	1907	2372	778	1098	420	1312	985	1700
Environment mean	2733	2699	2983	1682	2013	1892	1106	541	1037	985	

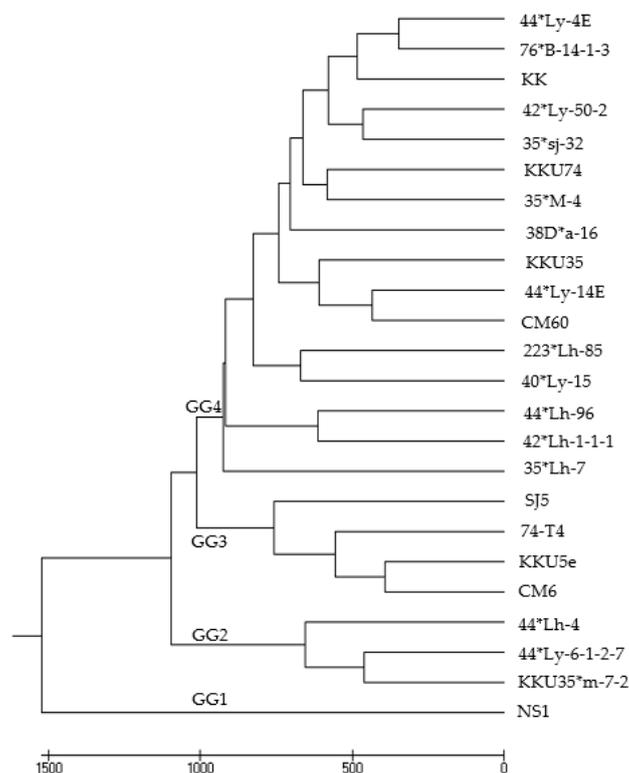
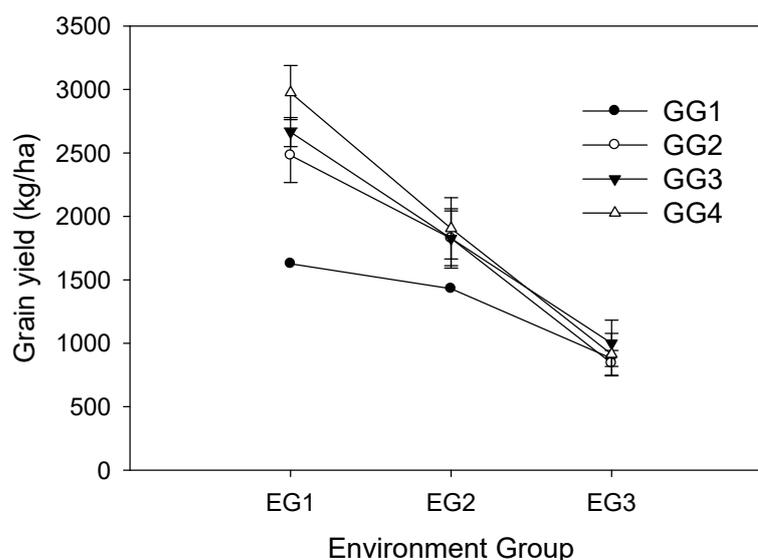
**Figure 2.** Genotype clustering based on the grain yields of 10 environments.

Table 6. Grain yields of all soybean genotypes in each environmental group (EG).

Genotype Groups	Genotypes	EG1	EG2	EG3
GG1	NS1	1627	1430	880
	Mean	1627	1430	880
GG2	44*Ly-6-1-2-7	2453	1721	757
	44*Lh-4	2282	2076	819
	KKU35*m-7-2	2709	1686	954
	Mean	2481	1827	843
GG3	KKU5e	2587	2086	976
	74-T4	2834	1801	1165
	SJ5	2613	1523	753
	CM6	2620	1892	1106
	Mean	2664	1826	1000
GG4	44*Ly-4E	2990	1671	853
	42*Ly-50-2	3122	1837	894
	38D*a-16	3138	1457	1086
	KKU74	3033	1750	1318
	76*B-14-1-3	3007	1659	734
	35*M-4	3039	1846	1120
	35*Lh-7	3116	1930	779
	35*sj-32	3356	1809	984
	44*Lh-96	2860	2204	824
	42*Lh-1-1-1	2819	2105	784
	44*Ly-14E	2684	1777	909
	223*Lh-85	3073	2412	741
	CM60	2606	1803	956
	KKU35	2574	1971	1053
	KK	3132	2065	831
	40*Ly-15	3047	2180	748
Mean	2975	1905	913	

**Figure 3.** Responses of four genotype groups (GGs) across three environmental groups (EGs). The bar depicts the standard deviation of each genotype in each group.

The high values of the environmental effects on grain yield and yield-related traits (Tables 3 and 4) necessitate the need to study the stability of genotypes across each environment based on the GGE bi-plot, which is made difficult due to the lack of homogeneous data (data not shown). The results suggest that the superior genotype of each environmental group can be determined based on its genotype responses. We may, therefore, conclude that the higher grain yields of the Group 4 genotypes, ranging from 2574 kg/ha (KKU35) to 3356 kg/ha (35*sj-32) with an average grain yield of 2975 kg/ha (Table 6), are suitable for production, as well as seed rotation, in these areas in both the wet and dry seasons.

4. Discussion

Soybeans are considered a minor crop in Thailand's vast agricultural production systems. Due to their ability to fixate nitrogen from the specific rhizobia bacteria in the soybean's root nodule, soybeans are suitable for growth in rotational or intercropping systems, which contribute to increased farmer income and improved soil health [19,20]. Thailand's two production seasons involve the common practice of planting soybeans in the wet season in the undulating topography of upland areas and the dry season in the lowland paddy fields. Each season presents several contrasting environmental factors that cause significantly different yields among soybean genotypes (Tables 2–4). In Northeast Thailand, sandy soil dominates both the upland field crops, such as cassava and sugarcane, as well as rice cultivated in the lowland rice paddies [21,22]. Sandy soil creates several problems with productivity due to its low fertility and water holding capacity, which adversely affect grain yields, particularly in the dry season (Table 2). Therefore, incorporating green-manure crops and plant residue in a rotational soybean cropping system represents an alternative way to improve an area's soil properties.

Special attention was determined to be necessary for creating a successful cropping calendar as soybeans represent a minor crop, compared with the magnitude of rice and sugarcane production. In Thailand's dry season, suitable sowing begins in early December due to the moisture content retained in the soil, where harvesting is expected to be completed in early April. Therefore, varieties with a moderated maturity of 90 to 100 days have proven suitable for cultivation. In our study, all breeding lines and check varieties were classified as having moderate maturity, except for the NS1 and KKU35 varieties, which represent early- and late-maturity varieties, respectively (Table 1). Early maturity varieties could complete the production process before the occurrence of growth-prohibiting stress factors. However, short-maturity genotypes have been associated with low yield potential due to their small plant canopy and short vegetative period [23]. In contrast, the late-maturity varieties achieved greater yields than those of the early- and moderate-maturity varieties. In the wet season, crop sowing begins in mid-June as rainfall is low, with harvesting being completed in mid-October in preparation for the upcoming cultivation of sugarcane. Planting soybeans during the wet season in the upland fields generally takes place during the sugarcane gap period between May and October, thereby making varieties with moderated maturity suitable for production. For several years, the KKU35 variety had been the most commonly planted soybean variety in Northeast Thailand; however, its production was limited due to its late maturity [24]. This level of maturity was limited as its harvest was interrupted by rain in the dry season and delayed in the wet season due to the land's preparation for sugarcane cultivation (Figure 4). Our results determined that the cropping system, environmental conditions, and maturity were important criteria for soybean cultivar selection in Thailand.

Based on the combined analyses of variance for each trait under all 10 environments and 24 genotypes, it can be indicated that the environment had a major effect on GY, DTF, plant height, first-pod height, number of nodes, number of pods, and 100 seed weight (Tables 3 and 4). In contrast, genotype had a major effect on the number of seeds/pod (Table 4). These results indicate that the cropping calendar, environmental condition, and crop maturity are important criteria for soybean production in Thailand due to the limitation of the expression of those traits [6–8]. Therefore, plant height and first-pod

height can be considered important traits for new soybean production systems in this particular area. Another aspect besides the aging society of soybean growers in Thailand is that harvest machinery should be applied due to the harvesting operation being one of the most labor-intensive operations. During the harvesting time, the important growth traits that influence soybean harvest losses, such as plant length and first-pod height [25,26], are critical criteria for selection. In addition, Weber and Fehr [27] reported stem losses of 12.2% due to a higher cutting height of 16.5 cm. In Thailand, a rice combine harvester was applied to soybean harvesting; however, seed was still lost because of the height of the combine cutterbar, and the lowest cutting height was adjusted for 15 cm, which limited harvesting soybean. The development of soybean cultivars for high yield needs to focus on both plant height and first-pod height.

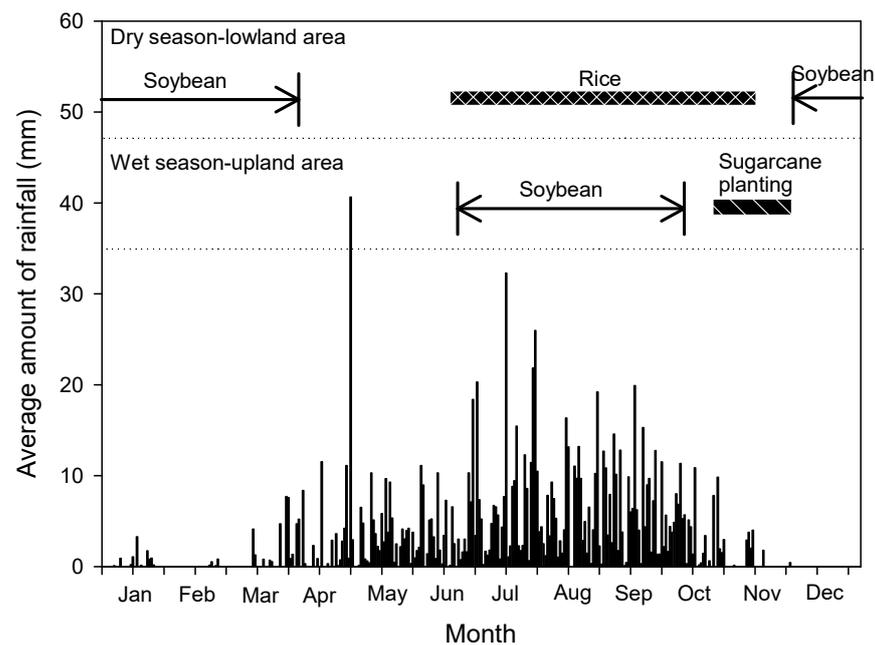


Figure 4. Average rainfall in the wet and dry seasons in Northeast Thailand in 2015–2019.

Soybean seeds are composed of roughly 20% lipids and are susceptible to qualitative deterioration processes via degradation of these compounds when improperly stored [28]. Long storage periods significantly reduce the rate of successful germination and negatively affect overall plant vigor [29,30]. Therefore, seed production is of critical importance for soybean production in Thailand. Traditional cropping systems involved seed rotation between seasons, in which seeds were rotated during the wet season in the north and the dry season in the central and northwest regions with the major varieties CM60 and SJ5 (Figure 5). These varieties have proven to be unsuitable in today's farming practice due to their poor germination under high soil moisture conditions. We determined, herein, that environmental factors significantly affect grain yield (Tables 2 and 4), thereby identifying the need to develop new soybean varieties. The study of the environmental groups (EGs) in both dry and wet seasons (Table 2 and Figure 1) demonstrated the necessity for duo-production locations.

Five top-yielding genotypes in GG4 (35*sj-32, 38D*a-16, 42*Ly-50-2, 35*Lh-7, and 223*Lh-85) can be recommended for narrow adaptation to specific environmental areas (Table 6). Based on GE1, which comprised both the dry season in lowland paddy fields and the wet season in upland sugarcane fields (fallow sugarcane), the contrasting environments of soybean production can be used year-round as duo-planting areas. The top five soybean breeding lines are well-adapted to these fallow sugarcane areas, roughly 0.24 Mha, and thus have the potential to enhance soybean productivity in Northeast Thailand.

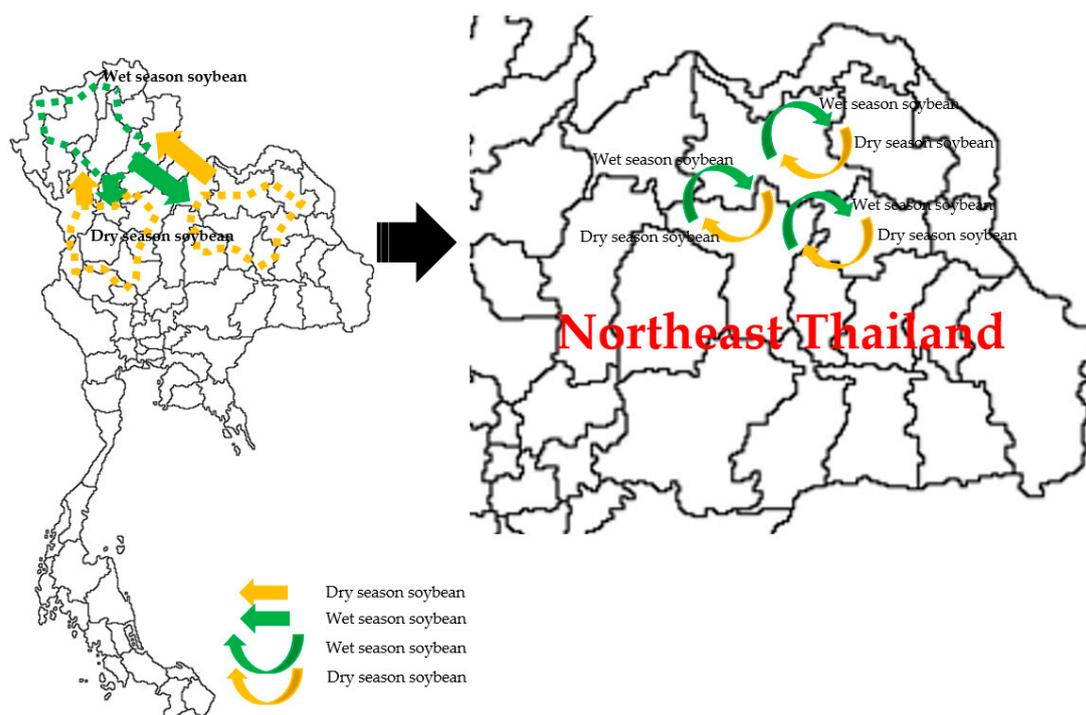


Figure 5. Duo-locations of soybean cropping production areas among national regions (left) and within Northeast Thailand (right).

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