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MULTI-ENVIRONMENTAL EVALUATION OF VEGETABLE SOYBEAN FOR ADAPTATION AND STABILITY IN BENIN

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ABSTRACT

Vegetable soybean (*Glycine max* L. Merr.) is a highly nutritious crop in Africa whose attributes make it a product of choice to formulate diets with numerous human health benefits. The crop is still novel in West Africa, but is making inroads in many countries of the region. The objective of this study was to evaluate selected vegetable soybean varieties for agronomic performance and stability for fresh pod yield across Benin. Thirty-five vegetable soybean varieties were planted at three locations, namely Calavi, Grand-Popo and Sèmè, for two seasons. There was a significant variation ($P < 0.05$; $P < 0.01$ and $P < 0.001$) among genotypes for most quantitative traits; with highly significant environmental ($P < 0.001$) and GEI effects on fresh pod yield ($P < 0.001$). Genotype *Maksoy 3N* (15.9 t ha^{-1}) had the highest fresh pod yield; while genotype *AGS466* was the most stable across environments. Based on GGE, Sèmè-2 was the ideal environment for growing vegetable soybean in Benin. The study confirmed that vegetable soybean is well adapted to be grown in Benin and varieties *AGS466, AGS346* and *Ashorowase* are candidates for wide cultivation in the country. Also, grain soybean varieties (*S1079-6-7* and *Maksoy 3N*) are well suited to produce vegetable soybean in Benin.

Key Words: *Edamame*, *Glycine max*, *Maksoy*, stability

RÉSUMÉ

Le soja vert (*Glycine max* L. Merr.), est un aliment très nutritif qui suscite un intérêt croissant en Afrique. Ses attributs nutritionnels en font une culture de choix pour la formulation des régimes alimentaires présentant de nombreux avantages pour la santé humaine. Cette culture est encore nouvelle en Afrique de l'Ouest, où elle en cours d'introduction dans plusieurs pays. L'objectif de cette étude était d'évaluer des variétés sélectionnées de soja vert pour leur performance agronomique et leur stabilité pour le rendement en gousses fraîches à travers le Bénin. Trente-cinq variétés de soja vert ont été plantées sur trois sites, à savoir Calavi, Grand-Popo et Sèmè, pendant deux saisons. Il y avait une variation significative (P < 0,05; P < 0,01 et P < 0,001) entre les génotypes pour la plupart des traits quantitatifs, avec des effets environnementaux (P < 0,001) et GEI très significatifs sur le rendement en gousses fraîches (P < 0,001). Le génotype *Maksoy 3N* (15,9 t ha^{-1}) a eu le plus haut rendement en gousses fraîches, tandis que le génotype *AGS 466* a été le plus stable à travers les environnements. Sur la base du GGE, Sèmè-2 était l'environnement idéal pour la culture du soja vert au Bénin. L'étude a confirmé que le soja vert est bien adapté pour être cultivé au Bénin et que les variétés *AGS 466, AGS 346* et *Ashorowase* peuvent être recommandées pour une large adoption. De même, les variétés de soja grain (*S1079-6-7* et *Maksoy 3N*) sont bien adaptées à la production du soja vert et sont recommandées au Bénin.

Mots Clés: *Edamame*, *Glycine max*, *Maksoy*, stabilité

INTRODUCTION

Vegetable soybean (*Glycine max* L. Merr.) is a type of soybean harvested and consumed prematurely, when the pods have full size seeds at one of the four uppermost nodes (Carson, 2010; Rao *et al.*, 2002). It is highly nutritious with lots of health benefits. On dry weight basis, 100 g of vegetable soybean provides 477 kilocalories, 41.3 g of proteins, 31 g of carbohydrates, and 21.9 g of lipids with cholesterol free fat (Takahashi and Ohyama, 2011).

The calorific value (energy) of vegetable soybean is about 6 times that of green peas, and it contains 60% more Ca, and twice more P and K than green peas (Ghobary and Shokr, 2010). Vegetable soybean is rich in ascorbic acid, but low in niacin (Masuda, 1991). It is also rich in fiber, zinc, folate, magnesium, isoflavones or phytoestrogens, which are polyphenols involved in regulation of cholesterol; decreasing the risk of cancer, hypertension, osteoporosis and heart diseases (Magee *et al.,* 2012). It contains numerous vitamins (A, B, C, E and K) (Poornima *et al.*, 2014), and it is equally richer in iron, vitamins B1 and B2 than green peas (Masuda, 1991).

Vegetable soybean, also known as "*edamame*" in Japan, is not yet known in many Sub-Saharan Africa countries such as Benin; despite the agro-ecological variability that makes the country suitable for growing various crops. Introduction of adaptable and stable *edamame* varieties in Benin will help to circumvent malnourishment, which affects more than 45% of children under five years (Fry, 2018).

Before introducing a new crop into a system, it is strategic to evaluate its adaptation in order to ensure that exotic species are able to withstand climatic and ecological conditions of its new habitat. Research on adaptation of vegetable soybean has been extensively carried out across the world; most especially in USA (Carter *et al.*, 2004; Khojely *et al.*, 2018), Uganda (Tsindi *et al.,* 2019) and Japan (Shanmugasundaram, 2001). However, there are no documented studies on *edamame* in West Africa. For *edamame* production to become commercially viable, growers need cultivars that will perform well in their environment, as yields and agronomic traits in crop varieties are often affected by the so-called genotype by environment interaction (GEI) (Agbahoungba *et al.*, 2017; Agoyi *et al.*, 2016, 2017; Baraki *et al.*, 2020). The objective of this study was to assess vegetable soybean cultivars for adaptation and yield stability in Benin.

MATERIALS AND METHODS

Genetic material. A total of 35 soybean varieties from various origins (Table 1) were used in this study; these include 28 true *edamame* varieties and 7 grain type soybean varieties selected based on their big seed size trait which has been reported as indication of suitability for use as *edamame* (Li *et al.,* 2019).

TABLE 1. Description of vegetable soybean genotypes used in the study

Accessions name	Origins	Seed coat colour	Flower colour
AGS423	AVRDC	Light green	White
AGS429	AVRDC	Light green	White
AGS432	AVRDC	Light green	White
AGS440	AVRDC	Green	White
AGS465	AVRDC	Light green	White
AGS466	AVRDC	Light green	White
AGS469	AVRDC	Light green	White
AGS470	AVRDC	Light green	White
AGS471	AVRDC	Brown	White
AGS472	AVRDC	Black	White
AGS346	AVRDC	Light green	Purple
ASHOROWASE	Japan	Light green	white
KUROMAME	Japan	Black	purple
DAIZU-22	Japan	light yellow	purple
JUUGOYAMAME	Japan	light yellow	purple
TOYOSAKAMAME	Japan	Brown	purple
SHOUNAI 2	Japan	Brown	purple
KOMAKI DADACHA	Japan	Brown	white
KANRO	Japan	Brown	white
HAKUCHO-EARLY	USA	Green	purple
BLACK JET	USA	Black	purple
JI LIN 15	USA	light yellow	white
ALTONA	USA	light yellow	purple
VITON	USA	light yellow	purple
CHINESE BLACK	USA	Black	white
ADA	USA	light yellow	white
JAPANESE	USA	Light green	white
TGX 2014-5GM	IITA (Zambia)	light yellow	purple
SC SAXON	Seedco (Zimbabwe)	light yellow	purple
TGX 2001-8DM	IITA (Zambia)	light yellow	purple
S1079-6-7	Seedco (Zimbabwe)	light yellow	purple
SC SENTINEL	Seedco (Zimbabwe)	light yellow	purple
MAKSOY 3N	Makerere University (Uganda)	light yellow	purple
TGX 2014-23FM	IITA (Zambia)	light yellow	purple
PANORAMA 357	Semillas Panorama (Colombia)	light yellow	purple

Experimental sites. The study was conducted in three sites representing the major agro-ecological zones where market gardening is well developed in Benin. These included Grand-Popo (Mono), Sèmè (Ouémé), and Calavi (Atlantique). Two consecutive seasons, namely the dry season running from January through March (2020_1) and the rainy season running from May through July (2020_2) were considered for this study. Climatic and soil characteristics of the experimental sites are provided in Table 2.

Experiment design and management. The experiment was laid in an alpha lattice design (7 blocks x 5 genotypes per block), with three replications in each of the three locations. Two seeds were planted per hole and the seedlings

TABLE 2. Soil and climatic characteristics of the experimental sites

Locations	Calavi_1	Calavi_2	Grand Popo_1	Grand Popo_2	Sèmè_1	Sèmè_2
	Soil characteristics					
pH water (1/2,5)	7.22	7.42	7.67	7.56	7.19	7.09
pH KCl (1/2,5)	6.64	7	7.27	7.17	6.99	6.97
Ca /(100 g)	4.93	4.67	1.23	7.20	2.71	2.81
Mg /(100 g)	0.61	0.45	0.79	0.81	0.22	0.23
K /(100 g)	0.12	0.21	0.11	0.23	0.11	0.09
Na /(100 g)	0.09	0.20	0.10	0.32	0.12	0.11
Cations /(100 g)	5.75	5.53	2.24	8.56	3.17	3.24
P (ppm)	103.50	92.26	49.80	135.28	103.89	71.84
	Climatic characteristics					
TM* (°C)	28.15	27.67	27.54	27.15	29.23	26.58
RH# (%)	84.61	90.69	80.58	85.90	81.65	98.85
PC£ (mm)	45.1	727	60.66	508.68	88.68	556.00
IC¥ (H)	425	383	443.00	429.00	406.35	365.34
Planting dates						
Planting dates (dd/mm)	2-Jan	6-Jun	31-Dec	9-May	10-Jan	13-May

*TM = Average temperature over the three months' experiment period; #RH = Relative humidity average over the three months experiment period; £PC = Cumulative precipitation over the three months experiment period; ¥IC = Cumulative insolation values over the three months experiment period

thinned to one plant per stand at 10 days after emergence. Each plot consisted of 4 rows of 5 m length. Line sowing followed 5 cm x 50 cm spacing. *Edamame* seeds were pre-mixed with biological N fixation inoculum , supplied by the Laboratory of Soil Microbiology and Microbial Ecology (LMSEM/FSA/UAC), prior to sowing. Inoculum was applied at the rate of 3.4 g inoculum per kg of seed, using the procedure recommended by Agoyi *et al.* (2016).

Weeding was done two times per season in Calavi and Grand popo, but three times in Sèmè where the field was invaded by sedges (*Cyperus* spp.). Fertiliser was applied first as poultry manure and later (4-5 weeks after sowing) as N:P:K 15:15:15 at a rate of 100 kg ha^{-1}. Soybean insect pests were controlled by applying Pacha 25 EC (Lambda-Cyhalotrin 10 g l^{-1} + Acetamiprid 15 g l^{-1}) at 1 L per hectare. *Cercospora* leaf blight and Frog-eye leaf controlled using a combination of fungicides (Mancozeb 80% + Topsin-M 70%), which was applied at 1 L ha^{-1}. The experiments were conducted under irrigation and plots were watered sufficiently twice per day on sandy soils and once a day on ferallitic soils, except whenever it rained.

Data collection. Data were collected from the two middle rows; and for each plot ten representative plants were selected randomly and tagged to collect data on: days to 50% flowering (DFR1), days to maturity R6 (DR6), number of nodes per plant at R6 (NNPR6), pod number per plant at R6 (PNPR6), and plant height at maturity (PHR6).

At physiological maturity, pods were harvested and carefully packed in sealed storage plastic bags. These were transported in a cooler bag containing refrigerated gels to the laboratory. These pods from each plot were weighed for fresh pod yield (FPY).

Data analysis. Data analysis consisted of a mixed-model analysis of variance (ANOVA) for each site and season separately, followed by a combined ANOVA between sites and seasons, thereafter AMMI and GGE analyses were performed. The R software (R version 3.6.1) (Team, 2019) was used for all statistical analyses. The models used were:

$Y_{ijk} = \mu + G_i + S_j + GS_{ij} + S/r_{jk} + \varepsilon_{ijk}$ (for single-site analysis) ………….…… Equation 1

$Y_{ijzhk} = \mu + G_i + L_h + S_j + GL_{ih} + GS_{ij} + LS_{hj} + GLS_{ihj} + E/r_{jhk} + \varepsilon_{ijhk}$ …… (for across-environments analysis) …………..... Equation 2

Where:

Y_{ijk} is the observed value from each experimental unit, μ population mean, L_h effect of the hth site, S_j effect of the jth season, S/r_{jk} effect of the kth replicate nestedto the jth season, E/r_{jhk} effect of the kth replicate nested to the jhth environment (environment = location by season), G_i effect of ith genotype, GS_{ij} interaction effect of ith genotype and the jth season, LS_{jh} effect of the jth season nested to the hth location, GLS_{ijh} interaction effect of ith genotype and the jhth environment (site per season) and ε_{ijkh} experimental error.

Genotype by environment effect was analysed for pod yield using AMMI analysis, performed from the mean data of all environments to detect the presence of GEI. Student-Newman-Keuls (SNK) test was performed to explain the significant differences among mean pod yields of the genotypes and environments. Significant means were separated using Fishers Least Significant Difference (LSD) at P<0.05.

RESULTS

Phenological and morphological parameters. The results from summary of ANOVA of single site analysis for all performance parameters measured on the plant and pod during both seasons are presented in Table 3. Genotype significantly (P<0.001) affected all performance parameters during both seasons in all sites, except at Calavi where genotype effect was not significant for DFR1. Season effect was also significant (P < 0.05) for all parameters in all sites, except at Grand-Popo and Sèmè, respectively, where PHR6 and NNPR6 were not significant.

In terms of interactions, genotypes interacted significantly with seasons for DFR1 (P < 0.001) in Sèmè and PNPR6 (P < 0.05) in Grand-Popo; and for PHR6 and PNPR6 (P < 0.01) in Calavi. Moreover, the single site ANOVA showed significant differences (P < 0.001; P < 0.05) among genotypes for pod length and width during both seasons in all sites.

Days to fifty percent flowering (DFR1) for the varieties tested ranged from 27 to 43, with a mean of 35 across genotypes and across sites (Table 4). Variety *Hakucho-Early* was the earliest to flower (27 DFR1 at Calavi, 28 at Sèmè and 33 at Grand-Popo) and S1079-6-7 was the latest to flower (40 at Grand Popo and Sèmè, and 43 at Calavi). Maturity period R6 stage (DR6) ranged from 62 to 84 at Grand Popo, 65 to 87 at Calavi and 68 to 89 at Sèmè. Variety *Hakucho-Early* was the earliest across sites (66 DR6), and *TGX 2001-8DM* and *Maksoy 3N* were the latest (84 DR6) (Table 4).

Plant height varied significantly from one site to another and from one season to another (P < 0.01), ranging from 31cm in Grand popo, 42 cm in Sèmè, and 45 cm in Calavi. Across sites, genotype *Maksoy 3N* (66 cm) was the tallest; while *Japanese* (29 cm) was the shortest with a mean of 39 across genotypes and across sites (Table 4).

TABLE 3. Summary of ANOVA results for single site analysis of all performance parameters measured on the plant and pod during two seasons in Benin

Sites	Sources	df	M.S.				
			DFR1	DR6	PHR6	NNPR6	PNPR6
Abomey_Calavi	Seasons	1	964.3*	373.3***	18621***	2312.6***	24836***
	Genotypes	34	219.7ns	374.8***	745**	51.9***	370***
	Interactions	34	187.5ns	5.7ns	115**	9.5ns	151**
	Residual	140	184.6	6	20	9.6	76
	Means		36.03	71.13	44.63	13.79	26.45
	CV (%)		38.71	11.56	34.68	38.02	60.28
	SEM		7.84	1.41	2.58	1.79	5.03
Grand_Popo	Seasons	1	88.08***	4601***	145.42ns	42.27*	445.9***
	Genotypes	34	27.79***	256**	135***	69.2***	289.2***
	Interactions	34	23.14***	37ns	72.08ns	10.94ns	52.5*
	Residual	140	4.01	37	50.32	8.3	34.5
	Means		36.67	68.17	31.11	7.04	18.33
	CV (%)		9.21	14.22	26.51	61.53	49.04
	SEM		1.16	3.51	4.10	1.66	3.39
Sèmè	Seasons	1	596.7***	2889.7***	353.2**	0.59ns	275.4*
	Genotypes	34	90***	174***	757.7***	85.91***	468***
	Interactions	34	18.6**	56.6**	115.5***	15.87*	125.9***
	Residual	140	9.8	27.6	33.9	10.96	53.9
	Means		33.26	73.40	42.29	10.02	21.92
	CV (%)		15.65	11.38	30.50	48.24	52.80
	SEM		1.81	3.03	3.36	1.91	4.24

DFR1 = Days to flowering R1, DR6 = Days to R6, PHR6 = Plant height to R6, NNPR6 = Node number per plant R6, PNPR6 = Pod Number per plant to R6, FPL = Fresh pod length, FPW = Fresh pod width, HFSY = 100 fresh seed weight,* Significant at 0.05, ** Significant at 0.01, *** Significant at 0.001

Across genotypes, number of nodes per plant (NNPR6) was 7 nodes in Grand popo, 10 in Sèmè, and 14 in Calavi (Table 4). Across sites, genotype *Maksoy 3N* had the greatest number of nodes (19), while *KOMAKI DADACHA* had the least number (7). Number of pods per plant (PNPR6) varied across sites and among genotypes (P< 0.05). Across sites, genotype *Maksoy 3N* had the highest number of pods per plant (43); while *KANRO* had the least number (Table 4).

Additive main effects and multiplicative interactions analysis. There was a highly significant (P<0.001) environmental and genotypic main effect on most performance parameters (Table 5). Genotype by Environment Interaction (GEI), effects were

TABLE 4. Means for phenological and morphological traits of 35 vegetable soybean genotypes across sites in Benin

Genotypes	DFR1				NNPR6				DR6				PHR6				PNPR6			
	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across
AGS423	34.7	35.7	32.2	34.2	14.8	5.1	7.7	9.2	67.0	62.8	72.0	67.3	45.0	28.8	36.6	36.8	30.7	13.2	16.8	20.2
AGS466	32.7	35.2	32.5	33.4	12.4	5.9	8.7	9.0	67.0	63.0	72.5	67.5	43.8	28.8	40.6	37.7	22.0	14.8	18.2	18.3
AGS469	37.0	36.5	33.8	35.8	13.0	6.7	8.4	9.4	67.0	66.8	74.0	69.3	47.0	34.0	41.7	40.9	18.0	15.5	15.5	16.3
AGS470	35.7	35.2	34.3	35.1	12.0	6.5	9.1	9.2	67.0	65.5	73.7	68.7	39.2	32.8	37.2	36.4	21.8	17.2	20.7	19.9
AGS471	34.8	35.0	31.5	33.8	13.1	5.4	9.2	9.2	67.0	64.2	71.8	67.7	35.9	28.8	36.9	33.8	23.6	13.7	15.4	17.5
AGS472	34.7	35.3	33.5	34.5	14.8	5.6	8.8	9.7	67.0	66.5	69.0	67.5	38.1	27.1	33.9	33.0	23.8	15.2	16.5	18.5
AGS346	34.3	35.7	32.5	34.2	13.5	5.5	9.2	9.4	67.0	67.8	72.5	69.1	47.1	33.8	40.8	40.6	23.6	13.9	19.6	19.1
AGS429	34.3	34.8	33.7	34.3	16.1	6.5	7.7	10.1	67.0	62.8	71.5	67.1	40.1	31.5	38.1	36.6	25.7	15.5	17.0	19.4
AGS432	33.0	34.3	31.8	33.1	10.8	5.2	6.2	7.4	69.0	62.2	66.0	65.7	31.5	31.3	32.3	31.7	21.8	18.7	15.6	18.7
AGS440	33.7	35.3	33.5	34.2	13.2	4.1	7.9	8.4	67.0	64.3	72.5	67.9	37.7	27.1	30.7	31.8	25.3	14.5	15.2	18.3
AGS465	34.2	36.8	33.5	34.8	9.6	5.1	9.2	8.0	67.0	69.7	75.8	70.8	51.2	29.4	45.8	42.1	14.0	16.8	17.5	16.1
TGX 2014-5GM	41.5	40.7	37.8	40.0	18.6	10.3	13.0	13.9	87.0	76.2	82.8	82.0	58.5	33.5	59.7	50.6	41.4	25.1	27.9	31.5
SC Saxon	39.2	38.8	33.8	37.3	13.9	8.5	14.5	12.3	67.0	76.8	73.7	72.5	38.7	35.3	51.9	42.0	22.9	19.8	30.7	24.5
TGX 2001-8DM	40.7	40.0	40.8	40.5	17.0	13.7	10.4	13.7	85.3	83.7	84.0	84.3	70.1	40.2	57.2	55.8	34.9	29.8	25.7	30.1
S1079-6-7	42.7	39.8	40.2	40.9	19.3	13.8	18.5	17.2	87.0	81.8	83.3	84.1	67.3	42.8	60.5	56.8	38.4	32.5	38.4	36.5
SC SENTINEL	39.5	40.5	38.8	39.6	18.4	9.5	13.9	13.9	87.0	77.0	79.2	81.1	54.2	34.5	47.9	45.5	49.6	26.2	38.1	38.0
Maksoy 3N	39.5	41.2	40.0	40.2	17.9	18.7	21.0	19.2	85.8	83.8	83.2	84.3	72.5	39.9	82.6	65.0	32.6	43.4	51.7	42.6
TGX 2014-23FM	39.8	40.8	38.0	39.6	16.2	10.9	11.1	12.7	87.0	79.7	68.8	78.5	60.3	39.1	55.9	51.8	35.6	24.8	25.3	28.6
KUROMAME	33.3	36.0	32.3	33.9	14.5	4.7	7.1	8.7	67.0	66.3	69.8	67.7	41.2	28.7	33.2	34.4	27.5	13.5	15.4	18.8
DAIZU-22	33.0	35.7	29.7	32.8	11.1	4.9	7.0	7.7	67.0	63.2	69.0	66.4	35.8	23.3	35.5	31.5	23.7	14.1	19.9	19.2
JUUGOYAMAME	33.0	36.5	31.8	33.8	13.6	5.5	8.3	9.1	67.0	63.7	69.8	66.8	41.1	33.6	44.7	39.8	25.2	15.8	18.8	19.9
ASHOROWASE	34.3	37.0	33.8	35.1	13.2	5.9	8.3	9.1	67.0	61.5	70.2	66.2	39.0	27.7	34.8	33.8	32.2	13.7	16.9	21.0
TOYOSAKAMAME	34.3	36.8	33.7	34.9	11.7	5.9	8.1	8.6	70.5	68.2	72.8	70.5	39.2	31.0	37.2	35.8	20.0	17.7	16.6	18.1
SHOUNAI 2	33.3	35.5	31.2	33.3	11.7	5.4	7.9	8.3	70.5	67.0	71.0	69.5	46.3	31.8	36.0	38.0	20.2	14.7	15.8	16.9
KOMAKI DADACHA	33.3	36.0	32.5	33.9	10.1	3.9	6.6	6.8	67.0	65.7	71.0	67.9	37.7	27.4	36.9	34.0	16.6	18.8	13.4	16.3
KANRO	31.5	35.2	30.3	32.3	10.1	4.5	7.0	7.2	67.0	64.3	70.8	67.4	33.9	26.4	31.4	30.6	17.5	16.5	13.1	15.7
Panorama 357	42.2	40.7	42.8	41.9	21.4	13.9	21.5	18.9	87.0	74.2	89.0	83.4	66.2	39.3	61.6	55.7	35.1	31.7	42.0	36.2
Hakucho-Early	27.0	33.8	28.3	29.7	12.1	6.2	8.0	8.8	65.5	63.8	68.7	66.0	36.5	28.0	40.4	35.0	20.5	15.0	19.4	18.3
Black Jet	34.0	35.0	32.7	33.9	11.6	5.5	10.5	9.2	67.0	65.0	74.7	68.9	41.6	24.9	36.6	34.4	21.7	13.5	23.5	19.5
Ji Lin 15	30.8	35.2	28.7	31.6	10.0	5.1	7.8	7.6	67.0	65.5	69.3	67.3	36.9	28.5	37.8	34.4	19.8	14.6	16.2	16.8
Altona	31.8	36.5	27.2	31.8	10.6	5.8	8.7	8.4	67.0	66.8	67.8	67.2	36.5	27.1	37.9	33.8	21.7	14.6	20.6	19.0
Vinton	32.5	35.0	28.8	32.1	14.0	5.9	11.8	10.6	67.0	64.5	77.5	69.7	35.6	27.8	40.6	34.7	29.4	14.6	26.1	23.3
Chinese Black	31.8	35.5	30.8	32.7	16.4	4.9	9.9	10.4	67.0	64.7	69.8	67.2	37.8	27.5	36.8	34.0	38.4	14.0	23.8	25.4
Ada	32.8	35.3	28.3	32.2	14.1	7.3	10.9	10.7	67.0	65.2	73.0	68.4	46.3	30.8	39.9	39.0	24.8	16.2	24.3	21.8

TABLE 4. Contd.

Genotypes	DFR1				NNPR6				DR6				PHR6				PNPR6			
	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across	Calavi	G-Popo	Seme	Across
Japanese	31.8	35.7	28.7	32.1	12.1	4.3	6.8	7.8	67.0	62.0	68.2	65.7	32.6	27.0	28.8	29.5	26.1	12.5	16.1	18.3
Mean	34.9	36.7	33.3	35.0	13.8	7.0	10.0	10.3	71.1	68.2	73.4	70.9	44.6	31.1	42.3	39.3	26.5	18.3	21.9	22.2
CV (%)	9.1	7.8	12	10.3	35	43	33	45.9	3.9	12	9.6	9.7	27	23.8	17	28.7	58	34.6	38	50.5
LSD(0.05)	7.4	6.7	9	4.77	11	7	7.8	6.23	6.58	18	16	9.09	28	17.2	16.7	14.9	35	14.7	19	1.81

DFR1 = Days to flowering R1, DR6 = Days to R6, PHR6 = Plant height to R6, NNPR6 = Node number per plant R6, PNPR6 = Pod Number per plant to R6
[a] Minimum significant difference between genotypes within both sites. [b] Minimum significant difference between genotypes across both sites. MSD: minimum significant difference according to Tukey's Post-Hoc test

also highly significant (P < 0.001) for all parameters. The first two interaction principal component axes were significant at (P < 0.001) for all performance parameters, except at DFR1, where PC2 was not significant (Table 5). The contribution of GEI to the total variation ranged from 11 to 24%, depending on the parameters (Table 5). The highest contribution to GEI was exhibited by PHR6; while NNPR6 had the lowest contribution. Environment' contribution to the total variation ranged from 5-38% (Table 5).

The largest environmental effect was observed for NNPR6; while the lowest was observed for DFR1. Genotypic contributions ranged from 7-44%. DR6 was the most affected by the genotypes and PHR6 was the least affected overall. (Table 5).

Additive main effects and multiplicative interactions analysis on pod yield. The combined AMMI analysis of variance for pod yield showed significant environment, genotype and GEI effects (P < 0.001) (Table 6). Environment, genotype and GEI effects contributed 25.91, 6.77 and 26.52, respectively to the total variation. GEI was further partitioned into five Principal Components (PCs) with PC1 and PC2 contributing 44.1 and 26.7%, respectively to the GEI (Table 6).

Genotypes mean fresh pod yield across environments. There were statistically significant (P<0.001) differences in fresh pod yields among genotypes. Eighteen genotypes, (Table 7) *viz. AGS 423, AGS432, AGS466, AGS472,AGS346, AGS 429,TGX 2014-5GM, Maksoy 3N, S1079-6-7, Ashorowase, Kuromame, Chinese Black, Japanese, Viton, Hakucho-Early, Komaki Dadacha, Juugoyamame, and Paronama 357* group mean produced fresh pod yield, above the average (10.3 t ha^{-1}) and the highest yield was recorded in *Maksoy 3N* (15.9 t ha^{-1}), followed by *AGS466* (13.5 t ha^{-1}), *S1079-6-7* (13.3 t ha^{-1}), *Kuromame* (13.0 t ha^{-1}), and *AGS472*

TABLE 5. Additive main effects and multiplicative interactions (AMMI) analysis of variance for phenological and morphological traits for vegetable soybean in Benin

Source	Df	DFR1			DR6			PHR6			PNPR6			NNPR6		
		ss	m.s	%SS	ss	m.s	%SS	ss	m.s	%SS	ss	m.s	%SS	ss	m.s	%SS
ENV	5.00	3020	605***	5.29	10700	2.15***	20.36	10700	2150***	33.6	32500	6500***	29.72	7150	1430***	37.6
REP(ENV)	12	2230	186***	3.91	1010	84***	1.92	1010	84***	3.17	2070	172***	1.89	196	16.4*	1.03
BLOCK(REP*ENV)	108	7280	67.4ns	12.77	2390	22.1*	4.54	2390	22.1ns	7.5	5860	54.3ns	5.36	1190	11*	6.25
GEN	34	6250	184***	10.96	23000	677***	43.77	2300	677***	7.22	30100	886***	27.53	6060	178***	31.87
GEI	170	13000	76.6*	22.8	7720	45.4***	14.69	7720	45.4***	24.24	19400	114***	17.74	2210	13***	11.62
PC1	38	10800	283***	18.94	3790	99.7***	7.21	3790	99.7***	11.9	9380	247***	8.58	970	25.5***	5.1
PC2	36	13500	37.5ns	23.68	1910	53***	3.63	1910	53***	5.99	5610	156***	5.13	591	16.4**	3.1
PC3	34	582	17.1ns	1.02	1080	31.7*	2.05	1080	31.7*	3.39	1930	56.8ns	1.76	336	9.87ns	1.76
PC4	32	236	7.38ns	0.41	794	24.8ns	1.51	794	24.8ns	2.49	1660	51.9ns	1.51	172	5.39ns	0.9
PC5	30	95.9	3.2ns	0.16	147	4.91ns	0.27	147	4.91ns	0.46	810	27ns	0.74	139	4.62ns	0.73
Residuals	300	18300	60.9		6410	21.4		6410	21.4		15100	50.2		2550	8.50	
Total	799	63100	79		59000	73.8		59000	73.8		124000	156		2160	27	

DFR1 = Days to flowering R1, DR6 = Days to R6, PHR6 = Plant height to R6, NNPR6 = Node number per plant to R6, PNPR6 = Pod Number per plant to R6, DF = Degrees of freedom; SS = Sum of squares; MS = Mean square; ENV = Environment; GEN = Genotype, Rep = Replication; GEI = Genotype environment interaction; PC = Principal component; * Significant at 0.05, ** Significant at 0.01, *** Significant at 0.001; ns = non-signiûcant

TABLE 6. Combined AMMI ANOVA for fresh pod yield of the vegetable soybean genotypes in Benin

Source	Df	SS	MS	%SS	% GEI	Accumulated %GEI
ENV	5	8950	1790***	25.91	.	.
REP(ENV)	12	890	74.1**	2.58	.	.
BLOCK (REP*ENV)	108	4040	37.4ns	11.69	.	.
GEN	34	2340	68.7***	6.77	.	.
GEI	170	9160	53.9***	26.52	.	.
PC1	38	4040	106***	11.69	44.1	44.1
PC2	36	2450	67.9***	7.09	26.7	70.8
PC3	34	1390	40.8ns	4.02	15.1	86
PC4	32	666	20.8ns	1.93	7.3	93.2
PC5	30	619	20.6ns	1.79	6.8	100
Residuals	300	9610	32		.	.
Total	799	44100	55.3		.	.

DF = Degrees of freedom; SS = Sum of squares; MS = Mean square; ENV = Environment; Rep = Replication; GEI = Environment genotype interaction; GEN = Genotype, GEI = Genotype environment interaction; PC = Principal component; ***: signiûcant at P < 0.001; ns = non-signiûcant

(12.7 t ha^{-1}). The lowest fresh pod yield was recorded in *AGS440* (6.5 t ha^{-1}) (Table 7).

AMMI bi-plot for high yielding and stable genotypes. The AMMI biplot was generated using the genotypic and environmental scores of the first two multiplicative components PC1 (44.1%) and PC2 (26.7%) to cross-validate the interaction pattern of the 35 genotypes accross the 6 environments (Fig. 1). Genotypes *AGS429* and *AGS472* expressed negatively against PC1 and positively against PC2; while Kuromame, Chinese Black and Komaki Dadacha expressed negatively against both PC1 and PC2. In contrast, *Maksoy 3N* and *AGS432* expressed positively against both components. These seven genotypes showed high interactive behaviour and contributed more to the exposed GEI. Black Jet, *AGS466*, SC Sentinel, Daizu-22, Toyosakamamae, Kanro, Shounai-2, *AGS471*, Hakucho-Early, Altona, Vinton, and Adaare genotypes were near to the origin and were stable genotypes. Hence, based on AMMI, genotype *AGS466* was identified as high yielding and the most stable.

Genotype and genotype by environment (GGE) biplot analysis

GGE biplot for yield (Mega-Environment). The GGE biplot grouped the test sites into four zones or mega-environments (Fig. 2: Zone 1 was represented by Sèmè1 and Grand-popo 2, Zone 2 represented by Sèmè 2, and Calavi 1, Zone 3 represented by Calavi 2 and Zone 4 represented by Grand-popo 1. The best performing genotypes per area were located at the top of the polygons. Genotype *Maksoy 3N* was the best in Zone 1, followed by *AGS472*. In Zone 2, the best genotype was *AGS466*. Two genotypes, namely; *AGS472* and Japanese were elites in Zone 3. Zone 4 was characterised by Chinese Black.

TABLE 7. Vegetable soybean genotypes pod yield across environments in Benin

Locations	Sèmè1	Sèmè2	Calavi1	Calavi2	Grand Popo1	Grand Popo2	GEI Mean
Seasons	1	2	1	2	1	2	
Genotype code	e1	e2	e3	e4	e5	e6	
AGS423	7.9	7.5	6.8	30.6	5.8	6.7	10.9
AGS466	10.6	12.8	21.5	19.1	7.6	9.6	13.5
AGS469	3.9	9.7	5.7	11.5	6.1	6.3	7.2
AGS470	9.7	9.4	4.7	14.6	5.9	8.2	8.8
AGS471	12.7	5.8	5.9	19.9	6.1	8.6	9.8
AGS472	11.0	16.8	5.9	31.8	5.2	5.8	12.7
AGS346	11.5	15.1	7.8	16.1	5.8	9.6	11.0
AGS429	4.7	12.2	5.9	31.9	5.2	5.4	10.9
AGS432	15.4	8.5	5.7	10.8	5.8	20.8	11.2
AGS440	4.3	10.4	5.7	9.9	3.3	5.2	6.5
AGS465	10.8	13.3	5.3	16.4	11.7	8.2	10.9
TGX 2014-5GM	15.5	12.4	6.9	14.5	8.9	10.7	11.5
SC Saxon	4.0	14.1	7.3	21.5	5.4	8.1	10.1
TGX 2001-8DM	10.7	10.2	5.8	11.7	3.7	12.9	9.2
S1079-6-7	12.6	18.7	8.3	19.4	5.2	15.4	13.3
SC SENTINEL	4.2	19.4	8.8	13.6	4.5	5.2	9.3
Maksoy 3N	30.1	13.2	8.4	17.0	6.9	20.0	15.9
TGX 2014-23FM	5.8	9.8	6.5	18.1	8.9	8.3	9.6
KUROMAME	6.4	9.3	10.1	26.8	20.4	4.8	13.0
DAIZU-22	11.5	9.7	5.1	19.4	6.9	4.3	9.5
JUUGOYAMAME	12.7	11.0	4.5	16.4	8.2	11.3	10.7
ASHOROWASE	9.7	14.9	5.2	25.9	6.1	13.8	12.6
TOYOSAKAMAME	6.4	10.7	4.3	18.2	8.5	6.6	9.1
SHOUNAI 2	10.6	11.8	4.9	17.3	5.5	5.5	9.3
KOMAKI DADACHA	9.5	7.8	6.7	15.7	19.6	5.3	10.8
KANRO	7.3	9.2	4.7	17.4	7.7	4.8	8.5
Panorama 357	10.4	14.7	6.4	13.4	7.8	11.2	10.6
Hakucho-Early	11.1	10.8	4.9	14.7	10.1	5.6	9.5
Black Jet	8.0	12.1	3.6	14.1	5.2	4.3	7.9
Ji Lin 15	10.4	8.8	5.7	12.5	10.5	4.2	8.7
Altona	10.0	10.2	5.0	13.6	6.4	4.9	8.3
Vinton	10.9	13.0	5.2	16.0	11.8	6.1	10.5
Chinese Black	3.1	11.5	5.6	19.5	22.5	6.6	11.4
Ada	6.4	7.7	4.2	15.1	8.5	6.8	8.1
Japanese	8.1	17.2	7.8	24.5	5.4	4.9	11.3
Env mean* (t ha^{-1})	9.7c	11.7b	6.5d	18.0a	8.1cd	8.2cd	
Grand mean (t ha^{-1})							10.3
SNK (<0.05)							41.7
CV (%)							62.4

*Means followed by same letter are significantly not different according to Student-Newman-keuls (SNK) test

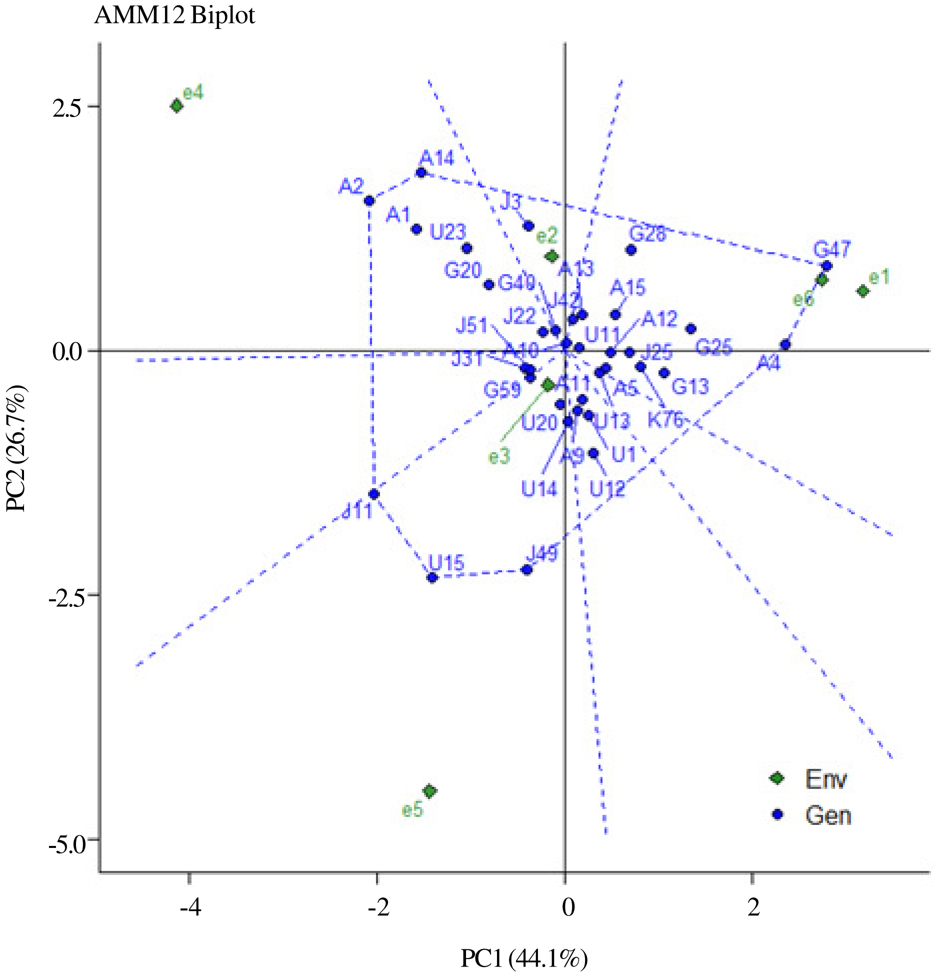

Figure 1. AMMI bi-plot to visualise the contribution of vegetable soybean genotypes to the GEI. Blue and Green dots stand for genotypes and environments, respectively. Genotypes*: A1: AGS423; A2:AGS429; A4: AGS432 ; A5: AGS440; A9: AGS465; A10: AGS466; A11: AGS469 ; A12: AGS470; A13: AGS471; A14: AGS472; A15: AGS346; G13:TGX 2014-5GM; G20: SC Saxon; G25: TGX 2001-8DM; G28: S1079-6-7; G40: SC Sentinel; G47: Maksoy 3N; G59: TGX 2014-23FM; J3: ASHOROWASE; J11: Kuromame ; J22: Daizu-22; J25: Juugoyamame; J31: Toyosakamame ; J42: Shounai-2; J49: Komaki Dadacha; J51: Kanro; K76 : Panorama 357; U1: Hakucho-Early; U11: Black Jet; U12: Ji Lin 15; U13: Altona; U14: Vinton; U15: Chinese Black; U20: Ada; U23: Japanese*

Environment (e): *e1:*Sèmè 1; e2: Sèmè 2; e3: Calavi1; e4:Calavi2; e5: Grand-Popo1; e6: Grand-Popo2

Which-won-where view of the GGE biplot
Scaling = 1, Centering = 2, SVP = 2

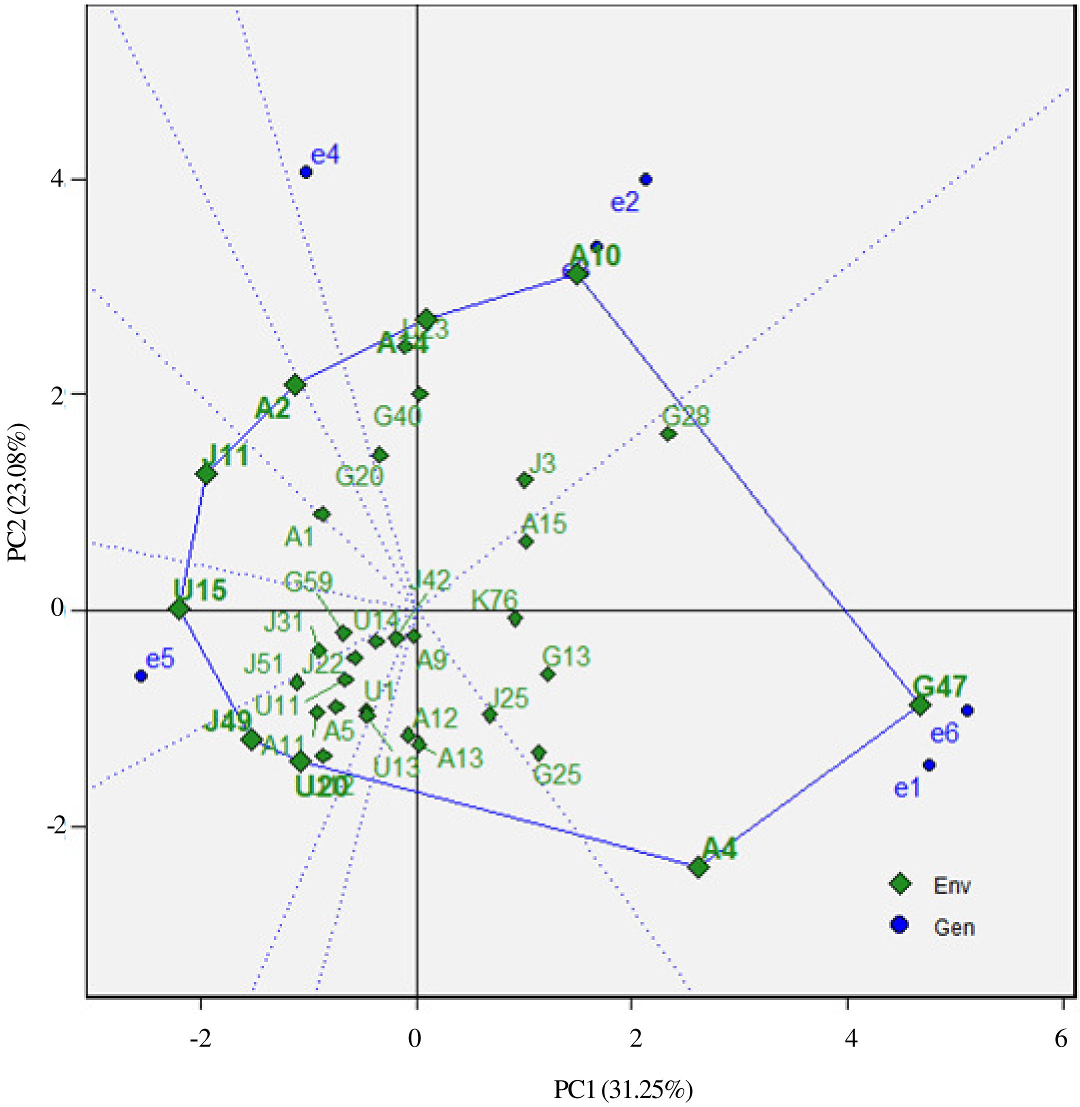

Figure 2. Polygon views of the GGE-biplot based on symmetrical scaling for the which-won where pattern for genotypes and environments. Green and blue dots stand for genotypes and environments, respectively. Genotypes: A1: AGS 423; A2:AGS 429; A4: AGS 432 ; A5: AGS 440; A9: AGS 465; A10: AGS 466; A11: AGS 469 ; A12: AGS 470; A13: AGS 471; A14: AGS 472; A15: AGS 346; G13:TGX 2014-5GM; G20: SC Saxon; G25: TGX 2001-8DM; G28: S1079-6-7; G40: SC Sentinel; G47: Maksoy 3N; G59: TGX 2014-23FM; J3: Ashorowase; J11: Kuromame ; J22: Daizu-22; J25: Juugoyamame; J31: Toyosakamame ; J42: Shounai-2; J49: Komaki Dadacha; J51: Kanro; K76 : Panorama 357; U1: Hakucho-Early; U11: Black Jet; U12: Ji Lin 15; U13: Altona; U14: Vinton; U15: Chinese Black; U20: Ada; U23: Japanese. Environment (e) : e1 : Sèmè 1; e2: Sèmè 2; e3: Calavi1; e4:Calavi2; e5: Grand-Popo1; e6: Grand-Popo2

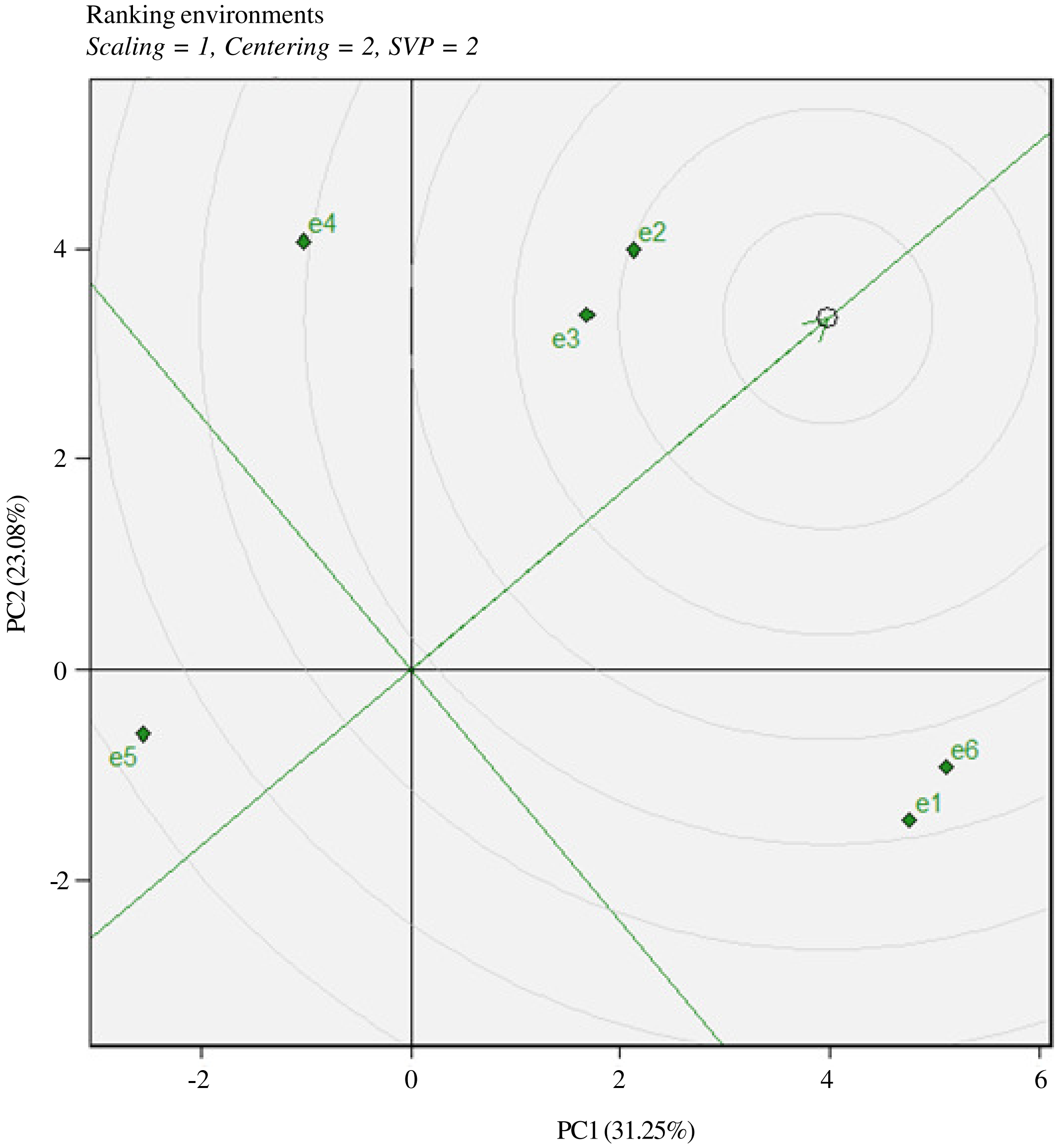

Figure 3 . GGE biplot for yield (Ranking Environment). Environnent (e): e1:Sèmè 1; e2: Sèmè 2; e3: Calavi1; e4:Calavi2; e5: Grand-Popo1; e6: Grand-Popo2

GGE biplot for yield (ranking environment). The "ideal'' or average environment is indicated by a circle with an arrow in it Figure 3. The ideal environment is the most discriminating of the other test environments in the present study it is e2 (Sèmè 2) that proved the most discriminating and representative for evaluating the performance of the tested genotypes.

DISCUSSION

Phenological and agro-morphological parameters. The single site analysis of variance showed significant differences for all vegetative traits. *Hakucho-Early* was the earliest to flower and mature within 66 Days (DR6) (Table 4). Similar earliness was observed in Uganda with the *edamame* genotype *AGS 329* (64 DR6) (Tsindi *et al.*, 2019). *Hakucho-Early* matured earlier than vegetable soybean tested in India (75 DR6) (Sharma and Kshattry, 2013; Poornima *et al.*, 2014). This is confirmatory for its selection and naming as *Hakucho-Early*. This variety could be recommended for late sowing under rain-fed *edamame* cropping. Also, the use of *Hakucho-Early* may present an economical advantage, as this genotype can be grown up to 5 times a year under irrigation.

Two grain type soybean genotypes, *TGX 2001-8DM* and *Maksoy 3N,* were the latest to mature (84 days after sowing); which was consistent with the observation made by Tsindi *et al.* (2019), who also found out that grain type genotype PI628919 was the latest maturing (106 days after sowing under Ugandan environment). However, our grain type soybean genotypes matured earlier than those tested in Uganda. On the contrary, Zhang and Kyei-Boahen (2007) reported much longer R6 maturity period (124 days) for *edamame* varieties in India; while Miles and Sonde (2002) observed 102 to 127 days to R6 in Washington.

As for plant height, Benin environments caused varieties to grow shorter than observed in Washington. For instance, Miles and Sonde (2002) observed plant heights ranging from 56 to 107 cm, while our study exhibited plant heights ranging from 29 to 66 cm. Also, the study found the number of pod per plant to vary from 16 to 43, depending on the genotype. This is consistent with observation made by Poornima *et al.* (2014), whereby number of pods per plant ranged from 22 to 44. Besides, fresh pod yield of the 35 genotypes ranged from 6.5 to 16 t ha^{-1}depending on the genotype. This value is low compared to the observation of Rao *et al.* (2002) and Lord *et al.* (2021) who reported fresh pod yields of 18.5 and 16.5 metric tonnes per hectare, respectively. However, our study showed slightly higher fresh pod yields compared to observations made by Shanmugasundaram *et al.* (1991), who reported yields ranging from 10 to 13 metric tonnes per hectare during spring, 6 to 9 during summer, and 6 to 10 t ha^{-1} during autumn in Taiwan. In Benin, our study showed yields ranging from 6.5 to 9.7 t ha^{-1} during the dry season, and 8.2 to 18 t ha^{-1} during the rainy season.

Overall, based on the maturity periods, with respect to plant heights, number of pods per plant and pod yields, our observations were quite consistent with results observed in previous studies (Shanmugasundaram *et al.*,1991; Miles and Sonde, 2002; Rao *et al.*, 2002; Zhang and Kyei-Boahen, 2007; Poornima *et al.*, 2014 ; Tsindi *et al.*, 2019; Lord *et al.*, 2021).

The fact that these genotypes matured earlier than the grain type soybeans, is indicative that Benin environments are suitable for *edamame* production. However, based on the relatively lower yields observed in Benin, compared to other *edamame* producing countries, it is recommended that further research be pursued to investigate the best agronomic practices that would boost the yield, in order to make the crop economically viable for sustainable introduction.

Additive Main and Multiplicative Interaction (AMMI) analysis. In addition to the usual ANOVA, the ANOVA of the AMMI model for all performance parameters and for pod yield in our study also detected significant variation ($P<0.001$) for the main and interaction effects, indicating the existence of a wide range of variation among genotypes, seasons, locations and their interactions (Table 7). The environment showed a large percentage of the genotype total sum of squares; indicating that the environments were diverse.

The fresh pod yield of the 35 genotypes across the growing environments, showed significant variation and the highest (18 t ha^{-1}) and lowest pod yield (6.5t ha^{-1}) were recorded in Calavi 2 and Calavi 1, respectively. As expected, the environment and GEI had greater contributions to the total variation than genetic effect for most measured traits. Gauch and Zobel (1996) reported that in standard multi environmental trials, the greater proportion of the treatment sum of square should be contributed by the environment.

The high environment and GEI effects observed in this study (Table 7) are attributable to variation in temperature from one season to another; and from one site to another. In addition, the nutrient composition of soils varies across sites. This ability of the environment to mask the genetic potential of the genotypes has a negative effect on selection and testing of vegetable soybean (Mebrahtu and Devine, 2008). Nevertheless, days to R6 (DR6) genetic effect was greater than environment and GEI effects; 44%, indicating that selection based on this trait has potential to enable achieve high genetic gain.

The AMMI containing PC1 (44.1%) *versus* PC2 (26.7%) are fully informative according to Gauch and Zobel (1996). Here, AMMI bi-plot showed that Sèmè 2 and Calavi 2 were favourable environments, yielding above average; while the other environments are unfavourable yielding below the average yield. AMMI bi-plot identified *AGS 466* as high yielding and most stable genotype.

The fact that the favourable environments were all from season 2, could be due to the higher relative humidity and rainfalls; and the insolation which was lower than at the other sites. For instance, Calavi 2 and Sèmè 2 had the highest rainfall (727 and 556 mm) and relative humidity (90.69 and 98.85%), respectively. Also, the insolation values were lower, 383 and 365.34 hours, respectively (Table 2). Guo *et al.* (2020), speculated that lower fresh pod yields could be attributed to differences in soil types and environmental factors such as higher temperature and precipitation during the early and late growth stages, in addition to management practices. Therefore, *edamame* production in Benin should target areas and seasons where rainfall is above 500 mm-700 mm and relative humidity is high at 90% during the cropping season and where insolation is less than 400 hours (climatic characteristics of the ideal zone Table 2).

Genotype and Genotype by Environment (GGE) biplot analysis. The scatter plot for fresh pods yield demarcated four mega environments (Fig. 3), which could be used as testing environments while conducting multi-environmental trials for preliminary or advanced yield trials. The comparison biplot (Fig. 4) showed *S1079-6-7* as the ideal genotype for fresh pods yield, which could be grown widely for achieving substantial yield. In addition, the other genotypes, *AGS466*, *Ashorowase* and *AGS346,* which were close to the ideal can also be considered well adapted to the Benin environments (Yan and Tinker, 2006). Sèmè2 was the ideal for most discriminating and representative of all the other environments.

CONCLUSION

Based on agronomical and yield performances, Benin environments are well suited for production of vegetable soybean, since the agroecologies in Benin are similar to those of many countries in West Africa. The varieties tested showed high genotype by environment interaction for both vegetative and yield traits. Varieties *S1079-6-7*, *AGS466, Ashorowase* and *AGS346* showed relatively high yields and high stability across environments, thus could be recommended for wide adoption in the Benin vegetable growing areas. Variety *Hakucho-Early* was the most precocious. The grain type soybean varieties showed high yield performance for fresh pod at medium maturity periods.

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