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RESEARCH ARTICLE

Impact of Genotype × Environment Interaction on Seed Yield and Pod Shattering of Soybean Genotypes in Nigeria

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ABSTRACT

Yield instability and pod shattering are the major problems associated with soybean production in Nigeria. To study Genotype × Environment interaction effects on seed yield and pod shattering behaviour of some soybean genotypes in Nigeria, an experiment was conducted in three (3) environments within the country. In each environment, the experiment was laid out in a randomized complete block design (RCBD) with three replications. During the harvest, pod shattering evaluation was conducted using the sun-dry method. Data were collected on seed yield and pod shattering percentage and analyzed using Additive Main Effect and Multiplicative Interaction (AMMI) and Genotype plus Genotype × Environment Interaction (GGE) bi-plot analyses. Genotypes NCRI SOYAC18, NCRI SOYAC78, NCRI SOYAC9, NCRI SOYAC20, NCRI SOYAC61, NCRI SOYAC22, NCRI SOYAC28 and NCRI SOYAC76, with yields above 1.23 ton/ha recorded high and stable yield across environments. For pod shattering resistance, nine genotypes (NCRI SOYAC3, NCRI SOYAC69, NCRI SOYAC77, NCRI SOYAC29, NCRI SOYAC9, NCRI SOYAC7, NCRI SOYAC67, NCRI SOYAC76 and NCRI SOYAC22) had stable pod shattering resistance across environments. Therefore, only three genotypes (NCRI SOYAC9, NCRI SOYAC22, and NCRI SOYAC76) were stable in both high yield and resistance to pod shattering. Consequently, any soybean breeding programme that involves high yield and pod shattering resistance could consider these three genotypes.

Keywords: Shattering, Soybean, Yield

1 Introduction

Soybean (*Glycine max* (L.) Merril), a member of fabaceae family is also referred to as 'Miracle bean' because of its high protein and oil content [1]. Its utilization in Nigeria is popular as a result of its tremendous potentials, which rank it higher than cowpea in the supply of high-quality protein [2]. It has also been established that soybean is an important source of domestic oil and among food legumes; it is only second to groundnut in terms of oil content [3] Soybean has average protein content of 40 % and about 20 % oil on a dry matter basis, which is 85 % unsaturated and cholesterol-free [4]

Soybean spread from China, its area of origin, has been mainly as a result of its adaptability. In Nigeria, Soybean is largely produced in the middle belt. However, its production in recent years has extended beyond these traditional areas to cover other Northern and Southern regions of the country, which were otherwise regarded as unsuitable or marginal for production[3] The cultivation of this crop in Nigeria has been faced with some challenges including pod shattering and yield instability. As in other crops, soybean phenotypic expressions vary with the environment [5]. Several genotypes have been evaluated in different environments for the identification of the best genotype suitable for a specific environment [5]

The cultivars of soybean grown today are due to intense genetic improvement, which is aimed at increasing grain yields per unit area. Such high-yielding cultivars need specific environmental conditions in order to express their full potential. Inconsistent genotypic responses to environmental factors like temperature, photoperiod, relative humidity, soil moisture content, soil type or fertility are a function of genotype × environment (G×E) interaction [1]. According to Adham *et al* [6], genotype × environment interaction is defined as the failure of genotypes to achieve the same relative performance in different environments. Therefore, the phenotypic response of any genotype in relation to others could be inconsistent, and this is demonstrated by changes of the relative genotype positions from one environment to the other. Good performance of stable genotypes is less dependent upon favourable environments, which makes their yield more predictable [7].

Pod shattering is the opening of mature pods along the dorsal or ventral sutures of the soybean pod and subsequent seed dispersal as the crop reaches maturity, as well as during harvest, resulting in seed loss [8]. In susceptible varieties, this can occur before harvest due to wind disturbances or during harvest as the harvesting implement move through the crop in dry weather conditions. Pod shattering in soybean may result to a yield loss that ranges from 34 % to 100 % [9]. It could be caused by the time of harvesting after maturity, environmental conditions, chemical composition of the pod wall; anatomical structure of the pod, and genetic factor of the variety [10]. In the major soybean production areas of Nigeria, the crop reaches maturity at the end of October or early November. Coincidentally, this is the period of rainfall cessation and the beginning of dry harmattan wind, with low relative humidity and rising temperatures. This creates a suitable condition for pod shattering.

An ideal soybean genotype is one that has the potentials to achieve the greatest yield and pod shattering resistance across many environments regardless of environmental conditions [11] This type of genotype is believed to possess genes that control soybean productivity and pod shattering resistance, regardless of biotic and abiotic stresses, and could be integrated in breeding programmes for the development of high yielding stable genotypes[12].

2 Literature Review

Yield stability is always considered as an important topic in plant breeding, especially with continuous variation in climatic conditions. Crop varieties may not show uniform performance across different environments due to G×E interactions [13]. A stable soybean cultivar usually possesses a relatively small seed yield fluctuations across locations. Crop yield varies due to suitability of genotypes to different growing seasons or environmental conditions. A particular genotype does not always express the same phenotypic traits under all environments and different genotypes respond differently to a particular environment. In order to attain high and stable yields, adequate choice of soybean cultivar is of upmost importance. According to Tyagi *et al.* [12], high yielding soybean genotypes are more likely to have lower stability and *vice versa*, that is, low yielding genotypes tend to have high stability across locations. Soybean breeders have traditionally stressed wide adaptation instead of specific adaptation in their breeding programmes and as a result selected genotypes that perform well over a wide range of climatic conditions. Wide adaptation offers stability against the variability inherent in an ecosystem, but a significant yield advantage in specific environment may be provided by specific adaptations.

2.1 Static Stability

Static stability is stability in the biological sense. It is the ability of genotypes to maintain uniform production in different environments, with low variation between them [14]. That is a stable genotype is the one possessing a constant performance irrespective of any changes in environmental conditions. This type of stability is rarely a favoured feature of crop genotypes, especially if genotypes with high phenotypic stability have low yield. As a result, this is not of interest to plant breeders to evaluate the phenotypic stability of the genotype performance, or other related random variables. Although, it is helpful to evaluate the phenotypic stability of the traits that should retain their levels such as stress characters like drought resistance, qualitative traits, or disease resistance [13].

2.2 Dynamic Stability

Dynamic stability refers to stability in the agronomic sense. This stability shows that the genotype positively responds to improvements in edaphic and climatic conditions of the environment and can perform above the mean in different environments [14]. The concept of dynamic stability is useful for quantitative traits such as yield and is of great interest to both plant breeders and farmers.

2.3 Statement of the Research Problem

The demand for soybean and soybean products in Sub-Sahara Africa outweighs its production. This leads to increased importation of soybean from the major producing countries of the world. Despite being the second highest soybean producer in Africa after South Africa, Nigeria still imported over 120,000 metric tons of soybeans, including raw soybeans, flours and meals. According to United States Department of Agriculture [15], soybean production in Nigeria in 2019/2020 farming season was on an average of 0.88 ton/ha, in farmers' field. This yield is not satisfactory owing to the fact that soybean has the potential to yield up to 8 tonnes per hectare[16]. Some genotypes grown in Nigeria have the potential to yield very high but are highly unstable as they are vulnerable to environmental changes and/or very susceptible to pod shattering.

Nowadays, the problems associated with soybean cultivation in Nigeria are climate change and scarcity of labour. Shortage of labour could delay harvesting, leading to yield losses through pod shattering. Pod dehiscence (shattering) is a major production constraint in the soybean production areas of the warm tropics. Seed losses of 50–100% are often associated with pod shattering during dry weather conditions in susceptible genotypes when harvesting is delayed after maturity. This loss of seed not only has a drastic effect on yield, but also results in the emergence of the crop as a weed in the subsequent growing season. In addition, shattering losses reduces yield potential that has already been achieved, and also leads to the loss of valuable genetic materials.

2.4 Justification for the Study

Increasing yield per unit area in soybean has received great attention among soybean breeders over the years; yet yield recorded in farmers' field in Nigeria is still far below the world average. This could be as a result of the use of varieties that are not stable and/or susceptible to pod shattering before harvest.

Among the several methods of controlling shattering in soybean, genetic improvement is the most reliable and environmentally friendly method [8]. In the hot tropics and areas where machines are used for harvesting, resistance to pod shattering is one of great economic benefits to farmers. A study involving soybean farmers in Benue State, Nigeria revealed that resistance to pod shattering was a prerequisite for the adoption of any variety by the farming communities [10]. Hence, there is need to develop improved genotypes with stable high yield and ability to stand in the field for relatively longer periods after maturity without shattering. The use of such genotypes is an important objective for sustainable production in the tropics. Krisnawati and Adie [10] have carried out commendable research to establish phenotypic markers for pod shattering resistance in soybean. However, none was able to establish environmental influence through multi environmental trails and stability studies. This study therefore seeks to address this gap. Enhancement in shattering resistance may promote productivity, harvesting of uniformly ripe seeds, efficiency of seed recovery and improved oil extraction. It will also promote adjustment in the time of harvesting and threshing; reduce cost of production, problem of volunteer plants and longevity of seed. Improved soybean varieties will lead to significant increase in our local production and provide raw materials to both livestock industries and other soybean processors.

2.5 Aim of the Study

The aim of this study, therefore, is to evaluate the impact of G×E interaction on soybean yield and pod shattering; and select best genotype(s) in terms of yield stability and pod shattering resistance across three environments.

3 Materials and Methods

3.1 Experimental materials

The study was conducted using 26 soybean genotypes, namely; NCRI SOY AC3, NCRI SOY AC7, NCRI SOY AC9, NCRI SOY AC10, NCRI SOY AC17, NCRI SOY AC18, NCRI SOY AC20, NCRI SOY AC22, NCRI SOY AC24, NCRI SOY AC25, NCRI SOY AC26, NCRI SOY AC28, NCRI SOY AC29, NCRI SOY AC61, NCRI SOY AC62, NCRI SOY AC63, NCRI SOY AC64, NCRI SOY AC65, NCRI SOY AC67, NCRI SOY AC68, NCRI SOY AC69, NCRI SOY AC73, NCRI SOY AC75, NCRI SOY AC76, NCRI SOY AC77, and NCRI SOY AC78.

3.2 Study locations

The study was conducted in three environments in Nigeria during 2020 cropping season. The first environment was Upper Niger River Basin Development Authority (UNRBDA) farm in Minna, Niger State (Latitude 9.6737^{o}N, Longitude 6.5109^{o}E); the second was UNRBDA farm in Chinka, Kaduna State (Latitude 9.0535^{o}N, Longitude 7.3026^{o}E); while the third environment was Teaching and Research Farm of the Department of Crop Science and Horticulture, Nnnamdi Azikiwe University, Awka, Anambra State (Latitude 6.3437^{o}N, Longitude 7.0938^{o}E).

3.3 Field experiment

The field experiment was laid out in Randomized Complete Block Design (RCBD) with three (3) replications in each of the environments. The gross plot size was 3 m × 2 m = 6 m^2; giving 4 ridges of 2 m long each. The net plot size was 1.5 m × 2 m = 3 m^2; to give 2 ridges of 2 m long each. Along each replication, gross plots were separated by a distance of 0.5 m, while an alley of 1 m separated one replication from the other. The total experimental area was 65 m × 11 m = 715 m^2.

Three (3) soybean seeds were sown per hill and later thinned down to one plant per stand. The planting distance used was 75cm × 20cm between and within rows, respectively. This gave a plant population of 66,667 plants/ha. Single super phosphate (SSP) was applied at the rate of 40kg/ha at 2 weeks after planting. Manual weeding was done at 2 and 6 weeks after planting. Data were collected on seed yield and pod shattering percentage.

3.4 Pod shattering identification

Pod shattering identification was done using sun-dry method [17]. Five plants were sampled per plot and four matured pods (brown or cream color) were harvested from each plant; giving a total of 20 pods. These pods were placed inside brown envelops and sun-dried for seven days. On the 7th day the number of shattered pods were counted and expressed in percentage. Pod shattering resistance or susceptibility of the genotypes was determined using the scoring rate according to Krisnawati and Adie[10] (Table 1).

Table 1: *Pod shattering scoring rate*[10]

Score	Description	Category
1	No pod shattering	Very resistant
2	< 25% pod shattering	Resistant
3	25 - 50% pod shattering	Moderately Resistant
4	51 - 75% pod shattering	Highly susceptible
5	> 75% pod shattering	Very highly susceptible

3.5 Data analysis

To determine the effect of genotype by environment interaction (GEI) and stability on yield and pod shattering, the data collected were subjected to Additive Main Effect and Multiplicative Interaction (AMMI) using the Breeding View of Breeding Management System (BMS); version 3.0.9 [18].
The AMMI model is $Y_{ij.} = \mu + g_i + e_j + \sum \lambda_k \, a_{ik} \, \gamma_{jk} + \varepsilon_{ij.}$
Where Y_{ij} is the mean of the ith line in the jth environment, μ is the grand mean, g_i is the genotype effect, e_j is the location effect, λ_k is the singular value for principal components k, a_{ik} is the eigenvector score for genotype i and component k, γ_{jk} is the eigenvector score for environment j and component k, and $\varepsilon_{ij.}$ is the error for genotype i and environment j. The result of the AMMI model analysis was interpreted by a biplot between Principal Component (PC) Axis 1 versus PC Axis 2.
Genotype plus Genotype × Environment Interaction (GGE) bi-plot analysis was used to show "which-won-where"; that is the best genotype in each environment, and it summarizes the GEI pattern of a multi environment yield trial data. GGE biplot is a graphical tool that displays, interprets and explores two important sources of variation, namely genotype main effect and GE interaction of MET data.

4 Results

4.1 Genotypes' Stability across the Environments for Seed Yield

The seed yield of the 26 soybean genotypes across the three locations ranged from 0.99 to 1.44 tons/ha (Table 2). Twelve genotypes gave higher seed yield than the grand mean (1.23 tons/ha). The environments' seed yield ranged from 1.03 tons/ha in Awka to 1.36 tons/ha in Chinka.

Table 2: *Seed yield of the genotypes across the three environments (ton/ha)*

Genotype	Minna	Chinka	Awka	Mean
NCRI SOYAC78	1.62	1.42	1.30	1.44
NCRI SOYAC18	1.54	1.07	1.34	1.31
NCRI SOYAC17	1.50	1.39	1.02	1.30
NCRI SOYAC69	1.35	1.60	1.05	1.33
NCRI SOYAC77	1.80	1.53	0.60	1.31
NCRI SOYAC73	1.30	1.29	0.93	1.17
NCRI SOYAC26	1.25	1.73	1.14	1.37
NCRI SOYAC29	1.52	1.15	0.97	1.21
NCRI SOYAC25	1.19	1.27	1.24	1.23
NCRI SOYAC28	1.32	1.40	1.04	1.25
NCRI SOYAC64	1.07	1.22	1.27	1.18
NCRI SOYAC65	1.00	1.24	0.74	0.99
NCRI SOYAC24	1.09	1.50	0.88	1.16
NCRI SOYAC3	1.35	1.04	0.99	1.12
NCRI SOYAC9	1.14	1.64	1.33	1.36
NCRI SOYAC7	1.27	1.22	1.05	1.18
NCRI SOYAC68	1.17	1.20	0.98	1.12
NCRI SOYAC20	1.35	1.37	1.12	1.28
NCRI SOYAC62	1.20	1.44	0.84	1.16
NCRI SOYAC63	1.24	1.45	0.90	1.19
NCRI SOYAC75	1.22	1.45	0.74	1.13
NCRI SOYAC10	1.10	1.23	1.07	1.13
NCRI SOYAC67	1.08	1.25	0.99	1.11
NCRI SOYAC76	1.35	1.49	1.07	1.30
NCRI SOYAC61	1.32	1.54	1.19	1.34
NCRI SOYAC22	1.32	1.27	1.13	1.24
Mean	1.29	1.36	1.03	1.23

Table 3 shows that the genotype with the least sensitivity to changes in environment was NCRI SOYAC18, as it had the lowest b value (-0.352). This genotype also had mean seed yield (1.31 ton/ha) greater than grand mean (1.23 ton/ha). However, NCRI SOYAC78, NCRI SOYAC9, NCRI SOYAC20, NCRI SOYAC61, and NCRI SOYAC22 also had low sensitivity to changes in the environments, with above average seed yield. All the high yielding and low sensitive genotypes also produced high static and dynamic stabilities (Table 3).

Table 3: *Sensitivity and stability coefficients for seed yield of the genotypes across three environments*

Genotype	Sensitivity	Mean	Static Stability	Wricke's Ecovalence	Mean square Deviation
NCRI SOYAC78	0.620	1.44	0.02528	0.03779	0.02774
NCRI SOYAC18	–0.352	1.31	0.05563	0.21520	0.10393
NCRI SOYAC17	1.337	1.30	0.06281	0.02754	0.01955
NCRI SOYAC69	1.528	1.33	0.07583	0.02861	0.01300
NCRI SOYAC77	3.380	1.31	0.39630	0.45381	0.11463
NCRI SOYAC73	1.189	1.17	0.04386	0.00649	0.00380
NCRI SOYAC26	1.413	1.37	0.09961	0.08837	0.08072
NCRI SOYAC29	1.013	1.21	0.07711	0.09601	0.09329
NCRI SOYAC25	0.007	1.23	0.00163	0.06126	0.00326
NCRI SOYAC28	1.107	1.25	0.03648	0.00077	0.00019
NCRI SOYAC64	–0.331	1.18	0.01026	0.11817	0.01399
NCRI SOYAC65	1.381	0.99	0.06258	0.01967	0.01201
NCRI SOYAC24	1.570	1.16	0.09978	0.07052	0.05323
NCRI SOYAC3	0.527	1.12	0.03916	0.07735	0.06185
NCRI SOYAC9	0.433	1.36	0.06351	0.13200	0.11590
NCRI SOYAC7	0.619	1.18	0.01330	0.01309	0.00389
NCRI SOYAC68	0.692	1.12	0.01423	0.00579	0.00007
NCRI SOYAC20	0.808	1.28	0.01966	0.00298	0.00057
NCRI SOYAC62	1.711	1.16	0.09141	0.03829	0.00911
NCRI SOYAC63	1.569	1.19	0.07682	0.02606	0.00760
NCRI SOYAC75	2.090	1.13	0.13281	0.07618	0.00627
NCRI SOYAC10	0.363	1.13	0.00616	0.02798	0.00449
NCRI SOYAC67	0.680	1.11	0.01802	0.01393	0.00864
NCRI SOYAC76	1.231	1.30	0.04598	0.00477	0.00195
NCRI SOYAC61	0.903	1.34	0.03130	0.01376	0.01423
NCRI SOYAC22	0.509	1.24	0.00956	0.01863	0.00375
Grand Mean		**1.23**			

In the AMMI bi-plot (Figure 1), The genotypes NCRI SOYAC78 (coded 1), NCRI SOYAC18 (coded 2), NCRI SOYAC17 (coded 3) NCRI SOYAC69 (coded 4), NCRI SOYAC77 (coded 5), NCRI SOYAC26 (coded 7), NCRI SOYAC28 (coded 10), NCRI SOYAC9 (coded 15), NCRI SOYAC20 (coded 18), NCRI SOYAC76 (coded 24), NCRI SOYAC61 (coded 25), and NCRI SOYAC22 (coded 26) recorded high yields, as they were located at the right side of the perpendicular line. Therefore, the genotypes located at the left side of the line were low yielding.

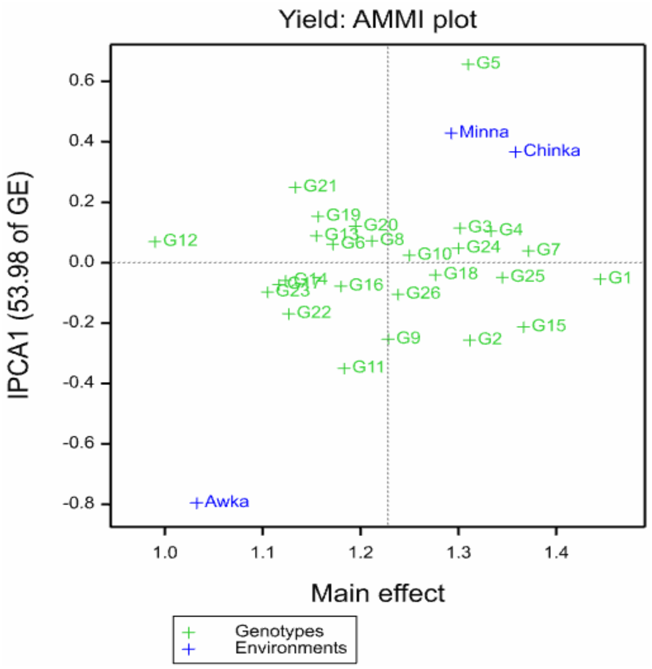

Figure 1: *AMMI Bi-plot for combined seed yield of the soybean genotypes in different environments*

Also, in the bi-plot, NCRI SOYAC20 (coded 18), NCRI SOYAC26 (coded 7), NCRI SOYAC78 (coded 1), NCRI SOYAC28 (coded 10), NCRI SOYAC76 (coded 24) and NCRI SOYAC61 (coded 25) are very close to the horizontal line near the zero point on IPCA1. Since these genotypes are located on the right side of the midpoint of the perpendicular line, they produced high and stable yield. The most unstable [genotype was NCRI SOYAC77 (coded 5), while the poorest in yield was NCRI SOYAC65 (coded 12).

The polygon view of the GGE bi-plot (Figure 2) shows that two environments were identified; with Minna and Chinka grouped as one environment, having NCRI SOYAC77 (coded 5), NCRI SOYAC17 (coded 3), NCRI SOYAC76 (coded 24), NCRI SOYAC29 (coded 8), NCRI SOYAC26 (coded 7), NCRI SOYAC28 (coded 10) and NCRI SOYAC69 (coded 4) as the best genotypes (winning genotypes). The best genotypes for the second environment (Awka) were NCRI SOYAC9 (coded 15), NCRI SOYAC22 (coded 26), and NCRI SOYAC9 (coded 15). The remaining sectors have no environment within them, meaning that the genotypes they contain were not the highest yielding at any environment.

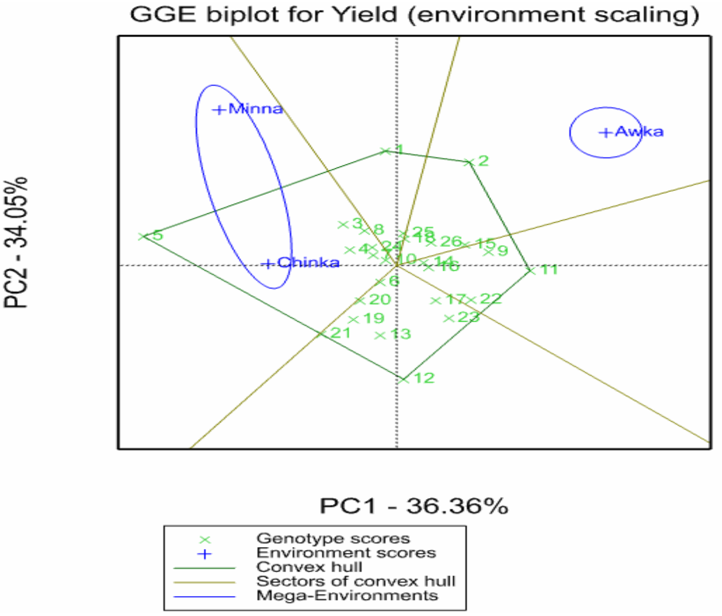

Figure 2: *GGE biplot for combined seed yield in different environments*

1 = NCRI SOYAC78; 2 = NCRI SOYAC18; 3 = NCRI SOYAC17; 4 = NCRI SOYAC69; 5 = NCRI SOYAC77; 6 = NCRI SOYAC73; 7 = NCRI SOYAC26; 8 = NCRI SOYAC29; 9 = NCRI SOYAC25; 10 = NCRI SOYAC28; 11 = NCRI SOYAC64; 12 = NCRI SOYAC65; 13 = NCRI SOYAC24; 14 = NCRI SOYAC3; 15 = NCRI SOYAC9; 16 = NCRI SOYAC7; 17 = NCRI SOYAC68; 18 = NCRI SOYAC20; 19 = NCRI SOYAC62; 20 = NCRI SOYAC63; 21 = NCRI SOYAC75, 22 = NCRI SOYAC10, 23 = NCRI SOYAC67; 24 = NCRI SOYAC76; 25 = NCRI SOYAC61; 26 = NCRI SOYAC22

1 = NCRI SOYAC78; 2 = NCRI SOYAC18; 3 = NCRI SOYAC17; 4 = NCRI SOYAC69; 5 = NCRI SOYAC77; 6 = NCRI SOYAC73; 7 = NCRI SOYAC26; 8 = NCRI SOYAC29; 9 = NCRI SOYAC25; 10 = NCRI SOYAC28; 11 = NCRI SOYAC64; 12 = NCRI SOYAC65; 13 = NCRI SOYAC24; 14 = NCRI SOYAC3; 15 = NCRI SOYAC9; 16 = NCRI SOYAC7; 17 = NCRI SOYAC68; 18 = NCRI SOYAC20; 19 = NCRI SOYAC62; 20 = NCRI SOYAC63; 21 = NCRI SOYAC75, 22 = NCRI SOYAC10, 23 = NCRI SOYAC67; 24 = NCRI SOYAC76; 25 = NCRI SOYAC61; 26 = NCRI SOYAC22

4.2 Genotypes' Stability across the Environments for Pod Shattering

The pod shattering rates of the genotypes across the three locations ranged from 6.39 % to 89.44 % (Table 4). The environments' mean ranged from 17.69 % in Chinka to 23.21 % in Minna.

Table 4: *Pod shattering percentage of the genotypes across the three environments*

Genotype	Minna	Chinka	Awka	Mean
NCRI SOYAC78	14.17	10.84	19.17	14.72
NCRI SOYAC18	34.17	35.83	32.50	34.17
NCRI SOYAC17	11.84	9.17	18.33	13.11
NCRI SOYAC69	20.50	24.17	20.84	21.83
NCRI SOYAC77	5.00	11.67	7.50	8.06
NCRI SOYAC73	11.67	5.00	15.84	10.83
NCRI SOYAC26	20.84	14.17	20.00	18.33
NCRI SOYAC29	10.00	8.33	10.00	9.44
NCRI SOYAC25	21.00	14.17	20.83	18.67
NCRI SOYAC28	21.84	10.83	27.50	20.06
NCRI SOYAC64	30.00	15.00	25.84	23.61
NCRI SOYAC65	29.50	25.84	35.00	30.11
NCRI SOYAC24	19.17	12.50	25.00	18.89
NCRI SOYAC3	15.83	25.00	15.00	18.61
NCRI SOYAC9	17.50	20.00	22.50	20.00
NCRI SOYAC7	6.67	10.00	9.17	8.61
NCRI SOYAC68	18.30	7.50	26.67	17.50
NCRI SOYAC20	15.84	11.67	20.84	16.11
NCRI SOYAC62	25.83	13.34	26.67	21.94
NCRI SOYAC63	94.17	85.00	89.17	89.44
NCRI SOYAC75	20.83	15.84	23.34	20.00
NCRI SOYAC10	22.00	6.67	23.34	17.33
NCRI SOYAC67	20.84	26.67	24.17	23.89
NCRI SOYAC76	5.84	5.84	7.50	6.39
NCRI SOYAC61	30.00	21.67	27.50	26.39
NCRI SOYAC22	9.17	13.34	9.17	10.56
Mean	21.25	17.69	23.21	20.72

Table 5, which is the table of regression coefficient (b), shows that NCRI SOYAC3, having a b-value of -1.951 was the most stable. This genotype was also resistant to pod shattering (Table 6).

Other resistant and stable genotypes were NCRI SOYAC69, NCRI SOYAC77, NCRI SOYAC29, NCRI SOYAC9, NCRI SOYAC7, NCRI SOYAC67, NCRI SOYAC76, and NCRI SOYAC22. Two genotypes (NCRI SOYAC29 and NCRI SOYAC76) had high static stability, while none had high dynamic stability (Table 5).

Table 5: *Sensitivity and stability coefficients for pod shattering percentage of the genotypes across three environments*

Genotype	Sensitivity	Mean	Static Stability	Wricke's Ecovalence	Mean square Deviation
NCRI SOYAC78	1.345	14.72	17.60	5.77	6.402
NCRI SOYAC18	–0.559	34.17	2.77	39.52	0.571
NCRI SOYAC17	1.413	13.11	22.20	11.57	12.604
NCRI SOYAC69	–0.691	21.83	4.12	44.38	0.634
NCRI SOYAC77	–0.999	8.06	11.34	66.15	6.787
NCRI SOYAC73	1.901	10.83	29.87	14.30	2.183
NCRI SOYAC26	1.224	18.33	13.18	5.85	2.512
NCRI SOYAC29	0.335	9.44	0.93	7.38	0.072
NCRI SOYAC25	1.347	18.67	15.17	5.51	1.450
NCRI SOYAC28	2.973	20.06	71.85	64.57	2.884
NCRI SOYAC64	2.445	23.61	59.96	65.57	24.679
NCRI SOYAC65	1.479	30.11	21.28	8.64	7.725
NCRI SOYAC24	2.126	18.89	39.12	24.51	6.238
NCRI SOYAC3	–1.951	18.61	30.80	136.8	0.938
NCRI SOYAC9	0.175	20.00	6.25	18.35	12.014
NCRI SOYAC7	–0.331	8.61	3.01	29.37	4.280
NCRI SOYAC68	3.299	17.50	92.35	93.33	11.28
NCRI SOYAC20	1.512	16.11	21.08	7.67	5.721
NCRI SOYAC62	2.619	21.94	55.75	47.41	2.253
NCRI SOYAC63	1.162	89.44	21.06	27.21	20.607
NCRI SOYAC75	1.340	20.00	14.58	2.11	0.533
NCRI SOYAC10	3.256	17.33	85.81	87.86	2.729
NCRI SOYAC67	–0.718	23.89	8.56	51.38	8.894
NCRI SOYAC76	0.225	6.39	0.92	9.18	1.041
NCRI SOYAC61	1.333	26.39	18.27	14.24	8.256
NCRI SOYAC22	–0.836	10.56	5.79	52.39	0.455

The AMMI bi-plot for pod shattering (Figure 3) shows the stable genotypes in terms of pod shattering across the three environments.

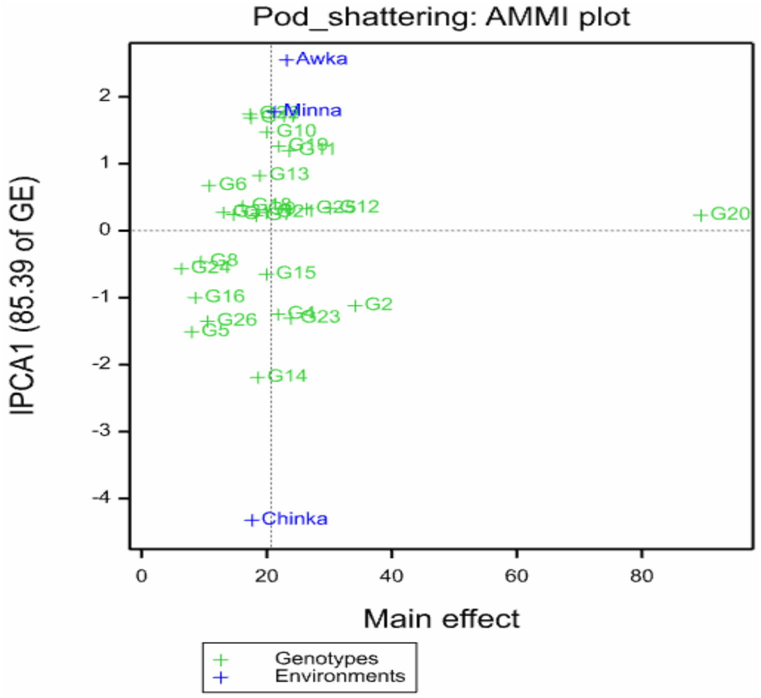

Figure 3 *AMMI Bi-plot for combined pod shattering percentage of the soybean genotypes in different environments*

In the bi-plot, the environments are located almost on the perpendicular line of the graph and thus have similar influence on pod shattering behaviour of the genotypes. Genotypes NCRI SOYAC63 (coded 20), NCRI SOYAC65 (coded 12), NCRI SOYAC61 (coded 25), NCRI SOYAC75 (coded 21), NCRI SOYAC25 (coded 9) and NCRI SOYAC17 (coded 3) were relatively stable, as they were located closer to the horizontal line of the bi-plot than other genotypes. Three of these stable genotypes (NCRI SOYAC75, NCRI SOYAC25, and NCRI SOYAC17) were resistant to pod shattering while two (NCRI SOYAC61 and NCRI SOYAC65) were moderately resistant. Genotype NCRI SOYAC63 was very highly susceptible to pod shattering (Table 6).

Table 6: *Genotype grouping based on combined pod shattering percentage across three environments*

Score	Description	Category	Genotypes
1	No pod shattering	Very resistant	Nil
2	< 25% pod shattering	Resistant	NCRI SOYAC78, NCRI SOYAC17, NCRI SOYAC69, NCRI SOYAC77, NCRI SOYAC73, NCRI SOYAC26, NCRI SOYAC29, NCRI SOYAC25, NCRI SOYAC64, NCRI SOYAC24, NCRI SOYAC3, NCRI SOYAC9, NCRI SOYAC7, NCRI SOYAC68, NCRI SOYAC20, NCRI SOYAC62, NCRI SOYAC28, NCRI SOYAC75, NCRI SOYAC10, NCRI SOYAC67, NCRI SOYAC76, NCRI SOYAC22
3	25 - 50% pod shattering	Moderately Resistant	NCRI SOYAC18, NCRI SOYAC65, NCRI SOYAC61
4	51 - 75% pod shattering	Highly susceptible	Nil
5	> 75% pod shattering	Very highly susceptible	NCRI SOYAC63

The GGE biplot (Figure 4) grouped the three environments into one environment, with NCRI SOYAC63 (coded 20), NCRI SOYAC18 (coded 2), NCRI SOYAC61 (coded 25), and NCRI SOYAC65 (coded 12) as the genotypes with the highest pod shattering percentage.

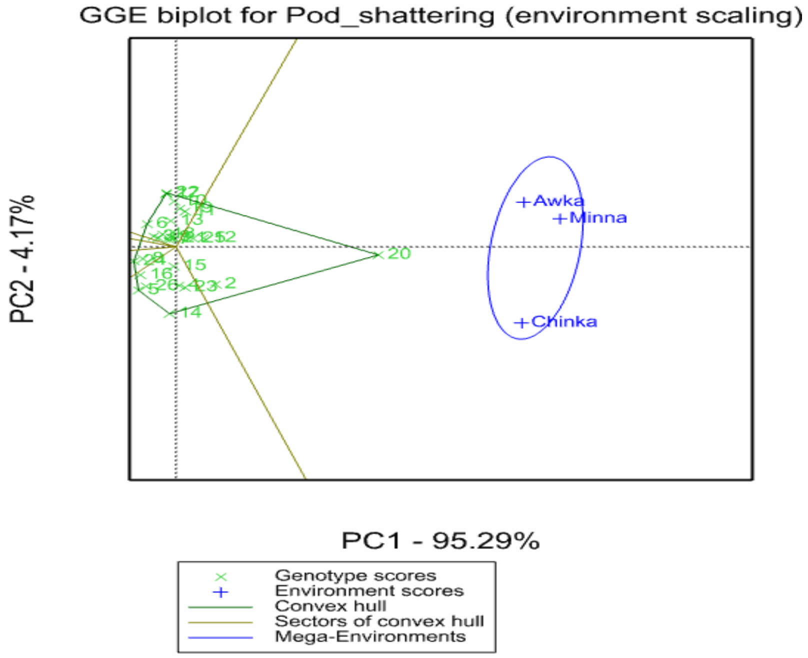

Figure 4 *GGE biplot for combined pod shattering in different environments*

1 = NCRI SOYAC78; 2 = NCRI SOYAC18; 3 = NCRI SOYAC17; 4 = NCRI SOYAC69; 5 = NCRI SOYAC77; 6 = NCRI SOYAC73; 7 = NCRI SOYAC26; 8 = NCRI SOYAC29; 9 = NCRI SOYAC25; 10 = NCRI SOYAC28; 11 = NCRI SOYAC64; 12 = NCRI SOYAC65; 13 = NCRI SOYAC24; 14 = NCRI SOYAC3; 15 = NCRI SOYAC9; 16 = NCRI SOYAC7; 17 = NCRI SOYAC68; 18 = NCRI SOYAC20; 19 = NCRI SOYAC62; 20 = NCRI SOYAC63; 21 = NCRI SOYAC75, 22 = NCRI SOYAC10, 23 = NCRI SOYAC67; 24 = NCRI SOYAC76; 25 = NCRI SOYAC61; 26 = NCRI SOYAC22

1 = NCRI SOYAC78; 2 = NCRI SOYAC18; 3 = NCRI SOYAC17; 4 = NCRI SOYAC69; 5 = NCRI SOYAC77; 6 = NCRI SOYAC73; 7 = NCRI SOYAC26; 8 = NCRI SOYAC29; 9 = NCRI SOYAC25; 10 = NCRI SOYAC28; 11 = NCRI SOYAC64; 12 = NCRI SOYAC65; 13 = NCRI SOYAC24; 14 = NCRI SOYAC3; 15 = NCRI SOYAC9; 16 = NCRI SOYAC7; 17 = NCRI SOYAC68; 18 = NCRI SOYAC20; 19 = NCRI SOYAC62; 20 = NCRI SOYAC63; 21 = NCRI SOYAC75, 22 = NCRI SOYAC10, 23 = NCRI SOYAC67; 24 = NCRI SOYAC76; 25 = NCRI SOYAC61; 26 = NCRI SOYAC22

5 Discussion

The high yielding and stable genotypes are able to replicate such performance across environments and also respond positively to improvements in soil and climatic conditions as a result of their high static and dynamic stabilities. According to Yohane *et al.* [14], high static stability points at the ability of the genotypes to give same performances across environments; and high dynamic stability shows that the genotypes positively responded to improvements in edaphic and climatic conditions of the environment and can perform above the mean in different environments. The concept of dynamic stability is useful for quantitative traits such as yield and is of great interest to both plant breeders and farmers. In the yield biplot, the environments are not located along the perpendicular line of the graph, which shows they provided greater variability than genotype differences, according to Khan *et al.*[19].

Although the high yielding genotypes are far below the yield genetic potential of soybean, which is 8 tonnes per hectare as stated by Ayalew *et al* [16], however, there is a significant improvement from the average soybean yield in Nigeria during 2019/2020 season as reported by USDA [15]. Including these genotypes in future soybean production and breeding programmes will definitely reduce the yield gap currently existing in soybean production in Nigeria.

In pod shattering of the genotypes, that both AMMI and GGE biplots revealed similar interactions among the environments, shows environment had little or no influence on the pod shattering pattern of the resistant genotypes. Therefore, genotypes provided greater variability than environmental differences. Furthermore, GGE biplot for pod shattering grouped the three environments into one, meaning they were similar. This is another proof to suggest that environment contributed a little to the variability observed in the pod shattering pattern of the genotypes. That is irrespective of environments, some soybean genotypes can still exhibit the same level of resistance or susceptibility to pod shattering. This is in agreement with the finding of Parker *et al.*[8] , which states that the genotypic characteristics of any genotype play a key role in the overall expression of pod shattering of that genotype; irrespective of climatic conditions.

6 Conclusion

Genotype × Environment interactions influenced both yield and pod shattering behaviours of the twenty-six soybean genotypes studied. Whereas environments provided greater variability in yield than genotype differences, the differences in the pod shattering rate were a function of genotype differences, with environments having little influence on the way the genotypes shattered. Genotypes with high and stable yield were NCRI SOYAC18, NCRI SOYAC78, NCRI SOYAC9, NCRI SOYAC20, NCRI SOYAC61, NCRI SOYAC22, NCRI SOYAC28 and NCRI SOYAC76. These could be selected for breeding of high yielding stable soybean varieties. NCRI SOYAC65 had the poorest yield, while NCRI SOYAC77 was the most unstable. As for pod shattering resistance, nine genotypes (NCRI SOYAC3, NCRI SOYAC69, NCRI SOYAC77, NCRI SOYAC29, NCRI SOYAC9, NCRI SOYAC7, NCRI SOYAC67, NCRI SOYAC76 and NCRI SOYAC22) had stable pod shattering resistance across environments and could be included in germplasm collection, as donor parents when breeding for pod shattering resistance in soybean. NCRI SOYAC 63 was both unstable and very highly susceptible to pod shattering. Therefore, out of the 26 genotypes, only three (NCRI SOYAC9, NCRI SOYAC22, and NCRI SOYAC76) were stable in both high yield and resistance to pod shattering. Consequently, any soybean breeding programme that involves high yield and pod shattering resistance could consider these three genotypes.

7 Declarations

7.1 Competing Interests

The authors declare no conflict of interest.

7.2 Publisher's Note

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