

Genotype by environment interaction for nut yield and associated traits in cashew (*Anacardium occidentale* L)

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Abstract

Cashew is cultivated in varied agro-ecological regions of India and yield levels vary with regions. Therefore, to identify stable genotype for yield, 18 genotypes were tested in four environments for nut yield and related traits during 2008 to 2018 in randomized block design with two replications. The data of 6th annual harvest and cumulative nut yield of six years was analyzed employing AMMI and GGE methods. Analysis of variance for 6th annual harvest indicated significant differences ($p < 0.01$) for eight traits. Environments varied significantly ($p < 0.01$) for seven traits. $G \times E$ interactions were significant ($p < 0.01$) for all traits. Analysis of variance for cumulative yield revealed significant variations between genotypes, environments, $G \times E$ interactions. About 95% of variability was captured by IPCA 1 (84.39%) and IPCA 2 (10.27%) in the $G \times E$ interaction. Genotypes, environments and $G \times E$ interaction were accounted for 16.18%, 4.50% and 77.22% respectively of total variation. The environment Pilicode discriminated better while Vridhachalam was representative. BPP-8 and Vengurla-7 were the winning genotypes in Bhubaneswar while Kanaka and Priyanka in Pilicode, Vengurla-4 in Jhargram and UN-50 in Vridhachalam. As per ASV (AMMI stability value,) K-22-1 was stable genotype followed by Bhubaneswar-1. As per YSI (yield stability index), Bhubaneswar-1 was stable and high yielding followed by K-22-1 and BPP-8. The study concludes that genotypes Bhubaneswar-1, K-22-1, BPP-8 may be suggested for cultivation in west and east coast regions of India.

Introduction

Cashew is cultivated in different agro-ecological regions of India and farmers in one region get more yield while in other regions less yield for the same variety. This is attributed to the influence of environmental conditions on the phenotypic expression of the varieties which is known as genotype $\times$ environment interaction ($G \times E$) effect. Earlier studies on cashew performance in diverse environments have shown significant $G \times E$ interaction effect for nut yield and its related trait (Aliyu et al. 2014; Madeni 2016; Bello et al. 2016; Bello et al., 2019). It is said that $G \times E$ interaction arises due to variations in the sensitivity of genotypes to the conditions in the environments they are grown (Falconer and Mackay, 1996) and it affects the efficiency of selection of superior genotypes (Ssemakula and Dixon 2007).

Most of the crop breeding programmes aim at assessing the yield performance of genotypes across several environments to identify genotype high yielding and adaptive to one specific environment or more than one environment (stable) and is an important approach for improving cashew nut production in India. The stable performance of genotypes in different environments decides the efficiency and success of selection (Otoo et al. 2006) and hence genotypes are evaluated in different environments to find out their adaptability and stability (Haldavankar et al. 2009). Many biometrical models are developed to estimate the $G \times E$ effect and stability performance of genotypes. Among them, additive main effect and multiplicative interaction (AMMI) analysis developed by Gauch and Zobel (1988) is a versatile statistical model as it has the capacity to capture good amount of $G \times E$ effect and makes the crop breeders to interpret the data proficiently and choose the variety suitable for each environment. Besides, GGE bi-plot analysis developed by Yan et al. (2000) is being used to supplement the AMMI analysis which helps in removing the effect of environment and integrates genotypic effect with $G \times E$ interaction effect (Aliyu et al., 2014). AMMI model estimates stability of the genotypes based on AMMI stability value (ASV) (Hagos and Abay 2013) which is calculated using IPCA1 and IPCA2 (interaction principal components axes 1 and 2, resp.) scores for each genotype (Purchase et al. 2000). The least ASV score of genotypes indicates genotypes are widely adapted. It is said that stability per se may not give considerable information regarding the level of yield (Farshadfar et al. 2011; Tumuhimbise et al. 2014) and thus they proposed yield stability index (YSI) that is calculated as sum of the rankings due to ASV scores and yield. The genotypes with lower YSI values denote high yielding and stable (Farshadfar 2008; Farshadfar et al. 2011; Baraki et al. 2014; Tumuhimbise et al. 2014; Bose et al. 2014). Hitherto, AMMI models were applied in cashew breeding programme in Nigeria (Aliyu et al., 2014) and Benin (Bello et al., 2019) and we are applying this model in Indian cashew breeding for the first time. With this backdrop, 18 cashew genotypes developed from different cashew research centers were evaluated in four environments in India for nut yield and related traits with the aim of understanding the influence of $G \times E$ effect and to identify stable and high yielding genotype for nut yield.

Results

Analysis of yield and associated traits of 6th annual harvest

Combined AMMI ANOVA

Combined AMMI analysis of variance over four environments for nine yield and related traits is presented in Table 2. Genotypes, excluding flowering laterals / m², showed significant differences ($P \leq 0.01$) for eight traits. Environments presented significant differences ($P \leq 0.01$ or $P \leq 0.05$) for the seven traits and did not show significant differences for nut weight and shelling percentage. Genotype and environment interactions ($G \times E$) were significant ($P \leq 0.01$) for all the traits. The variation contributed by the effect of genotype varied from 6.39% (flowering laterals / m²) to 37.56% (nut weight) while the variation due the effect of the environment was between 4.3% (shelling percentage) and 44.99% (tree height). The sums of variations of IPCA1 and IPCA2 ranged from 83.66% (shelling percentage) to 96.91% (sex ratio).

Ranking of genotypes in each environment for traits

The ranking of genotypes in each environment for the data of nut yield and other traits taken during 6th annual harvest is presented in *Table 3 (supplementary file)*. It showed that BPP-8 ranked first for nut yield with mean of 16.34 kg /tree, VRI-3 ranked first for number of flowering laterals per sqm with mean of 23.29, Kanaka ranked first for sex ratio with mean of 0.90 and Vengurla-7 ranked first for stem girth with an average of 76.25 cm in

the environment Bhubaneswar. VRI-3 ranked first for plant height with a mean of 3.01m and Madakkathara-1 ranked first for tree spread with a mean of 4.30m in the environment Vridhachalam. Priyanka ranked first for nut weight with a mean of 10.88g in the environment Pilicode. Madakkathara-1 ranked first for nuts per panicle with an average of 13.04 in Pilicode. VRI-3 ranked first for shelling percentage with a mean of 35.83% in Jhargram.

Table 1

List of cashew genotypes evaluated in MLT-V and their source

S.No.	Genotype	Source
1	BPP-8	Cashew Research Station, Bapatla
2	Bhubaneswar-1	Cashew Research Station, OUAT, Bhubaneswar
3	Madakkathara-1	Cashew Research Station, Madakkathara, KAU
4	Madakkathara-2	Cashew Research Station, Madakkathara, KAU
5	K-22-1	Cashew Research Station, Madakkathara, KAU
6	Dhana	Cashew Research Station, Madakkathara, KAU
7	Kanaka	Cashew Research Station, Madakkathara, KAU
8	Priyanka	Cashew Research Station, Madakkathara, KAU
9	Amrutha	Cashew Research Station, Madakkathara, KAU
10	Vengurla-4	Regional Fruit Research Station, Vengurla, KKV
11	Vengurla-7	Regional Fruit Research Station, Vengurla, KKV
12	VRI-3	Regional Research Station, Vridhachalam, TNAU
13	NRCC Sel-2	ICAR-Directorate of Cashew Research, Puttur, Karnataka
14	Ullal-3	Agricultural Research Station, Ullal, Karnataka
15	Ullal-4	Agricultural Research Station, Ullal, Karnataka
16	UN-50	Agricultural Research Station, Ullal, Karnataka
17	Goa-1	ICAR-CCARI, Goa
18	Bhaskara	ICAR-Directorate of Cashew Research, Puttur, Karnataka

Table 2

Combined AMMI analysis of variance over four environments for traits (data of 6th annual harvest)

Source	DF	Flowering Laterals/m ²	% Variation	Stem Girth (cm)	% Variation	Tree Height (m)	% Variation	Nut Weight (g)	% Variation	Nuts /panicle	% Variation
Genotypes (G)	17	19.6ns	6.39	175.8**	15.82	0.833**	8.37	5.691**	37.56	10.14**	16.29
Environments (E)	3	627.2**	36.12	1693.9**	26.90	25.374**	44.99	15.287ns	17.81	53.95*	15.30
Blocks	5	135.1**	10.38	368**	9.97	5.311**	12.55	12.043**	18.70	20.57**	7.78
G x E	51	30.4**	29.77	121.0**	32.66	0.691**	20.83	1.216**	24.08	10.70**	51.58
IPCA1	19	48.1**	58.99	210.0**	64.67	1.350**	72.77	1.926**	59.00	19.45**	67.75
IPCA2	17	28.1**	30.75	73.8**	20.32	0.380**	18.33	0.921**	25.25	6.49**	20.22
Residual	15	10.6	10.25	61.7	14.99	0.210	8.94	0.651	15.75	4.38	12.03
Error	68	13.3	17.35	41.3	14.86	0.330	13.24	0.070	1.84	1.41	9.04
DF: degree of freedom, G x E: genotype by environment interaction, IPCA: interaction principal component analysis, * significant at $P \leq 0.05$ **: significant at $P \leq 0.01$, ns: non-significant											

Table 2
Contd: Combined AMMI analysis of variance over four environments for traits of 6th annual harvest

Source	DF	Shelling Percentage	% Variation	Sex Ratio	% Variation	Canopy Spread (m)	% Variation	Nut Yield (kg/tree)	% Variation
Genotypes	17	7.074**	18.44	0.03547**	15.94	1.466**	15.99	12.12**	13.51
Environments	3	9.412ns	4.32	0.36939**	29.28	12.771**	24.58	117.54**	23.11
Blocks	5	4.690**	2.88	0.01384**	1.45	1.408**	3.61	0.84ns	0.22
G x E	51	8.349**	65.28	0.03627**	48.89	1.125**	36.81	14.76**	49.35
IPCA1	19	12.326**	55.00	0.06615**	67.94	1.928**	63.87	23.67**	59.74
IPCA2	17	7.227**	28.86	0.03153**	28.97	0.916**	27.14	12.33**	27.84
Residual	15	4.583	16.13	0.00378	3.08	0.344	8.99	6.23	12.42
Error	68	0.872	0.46	0.00247	4.40	0.435	19.00	3.10	13.81
DF: degree of freedom, G x E: genotype by environment interaction, IPCA: interaction principal component analysis, **: significant at $P \leq 0.01$									

Analysis of cumulative nut yield

Combined AMMI ANOVA

Combined AMMI analysis of variance over four environments for cumulative nut yield per tree of six years is presented in Table 4. The mean squares due to genotypes, environments, genotype and environment interactions (G x E) were all significant ($P \leq 0.01$). The variation explained by genotype was 16.18% out of the total variation (Table 5) while the variation due to environment was 4.5% and the variation due to G x E was 77.22%. The sum of variations of IPCA1 and IPCA2 is about 94.66%.

Table 4
Combined AMMI analysis of variance for cumulative nut yield

Source of variation	DF	SS	MS	F Value	F pr
Genotypes (G)	17	1662	97.70**	36.59	< 0.001
Environments (E)	3	462	153.8**	17.67	< 0.001
Blocks	5	35	8.7**	3.26	0.0166
G x E	51	7932	155.5**	58.22	< 0.001
IPCA1	19	6694	352.3**	131.88	< 0.001
IPCA2	17	815	47.9**	17.94	< 0.001
Residual	15	423	28.2	10.57	< 0.001
Error	68	182	2.7		
Total	143	10272	71.8		
		R² = 0.99	CV(%) = 7.39	Grand mean = 18.01	

DF: degree of freedom, SS: sum of squares, MS: mean squares, G x E: genotype by environment interaction, IPCA: interaction principal component analysis, **: significant at $P \leq 0.01$, CV = coefficient of variation, R^2 = coefficient of determination.

Table 5
Variation Explained (%) by each source of variation for cumulative nut yield

Source of variation	SS	Variation Explained (%)
Genotypes (G)	1662	16.18
Environments (E)	462	4.50
Blocks	35	0.34
G x E	7932	77.22
IPCA1	6694	84.39
IPCA2	815	10.27
Residual	423	5.33
Error	182	1.77
Total	10272	100.00
DF: degree of freedom, SS: sum of squares, G × E: genotype by environment interaction, IPCA: interaction principal component analysis		

GGE bi-plot analyses

Discriminitiveness vs. representativeness

The ability of environment to differentiate genotype is called discriminativeness while the ability of environment to represent all the environments evaluated is known as representativeness. These two attributes are illustrated in the Fig. 2a GGE bi-plot. Lines that connect between origin and environment are the environment vectors. Environment vectors with shorter length denote less discriminating ability while those with longer vector length show higher discriminating ability. In this study, the environment Pilicode showed higher discrimination of genotypes compared to other three environments. The line with single arrow passing through the origin and the small concentric circle (indicates average value of the environment) is referred to as average environment coordination (AEC) abscissa or average environment axis (AEA). An environment that has a small angle between its vector and the AEA is more representative (Yan and Tinker 2006). Furthermore, the association between two environments is explained by the cosine of the angle between their vectors. Acute angle between two environment vectors denote positive association or similarity while obtuse angle mean negative association and right angle depict no association. In our study, the environment Vridhachalam is found to be more representative as it formed smaller (acute) angle with AEA. The angles between the vectors of Vridhachalam and Jhargram, Jhargram and Bhubaneswar, Bhubaneswar and Pilicode were acute suggesting their effects were similar for genotype expression. The angle between Pilicode and other three environments was obtuse displaying negative correlation or dissimilarity.

Comparing genotypes with ideal genotype

Ideal genotype is the genotype that has both greater mean performance as well as greater stability for a specific trait evaluated over mega-environment (Yan and Tinker 2006). It is represented by the point on the AEC abscissa at the center of concentric circles in the GGE bi-plot. The genotypes that are located close to the ideal genotype are considered as the best. In the present study, genotypes Madakkathara-1, BPP-8 and Bhubaneswar-1 were considered as best for cumulative nut yield / tree (Fig. 2b).

Means vs. stability

The GGE bi-plot of means versus stability gives information on mean performance of genotypes and their stability. It consists of two lines viz., i) the average environment axis (AEA) or average environment coordination (AEC) abscissa and ii) the AEC ordinate. AEA is the line with a single arrow that passes through the origin of bi-plot and the theoretical average of the environment denoted by small circle. The direction of the arrow on the AEA indicates greater mean performance for the trait or main effect of genotype (Yan 2001). Genotypes situated towards the direction of arrow indicate greater mean values while those located in the opposite direction of arrow denote lower mean values. Thus in the present case variety Kanaka has greater mean value while UN-50 has lowest mean value (Fig. 3a). The AEC ordinate also passes through the origin and is perpendicular to the AEA. The two ends of this ordinate suggest poor stability or greater G x E effect in two directions. The relative lengths of projections of genotypes from the AEA measure their stability. Shorter the projection of genotype greater is the stability and vice-versa (Yan and Kang 2002). In the present study, genotypes Bhubaneswar-1 and K22-1 presented shorter projections suggesting their greater stability for nut yield /tree (Fig. 3a). Whereas the genotype Priyanka displayed more projection length showing poor stability or greater variability.

Which–won–where

Which –won –where pattern of genotype is given by the polygon view of the bi-plot and it describes the performance of genotypes according to environments (Fig. 3b). The polygon is constructed by drawing lines on genotypes that are located farthest from the origin of bi-plot and ensuring falling of all other genotypes inside the polygon. Genotypes which perform well in a particular environment are called winning genotypes. The polygon is divided into different sectors by the lines drawn from the origin of the bi-plot and perpendicular lines drawn from the origin to the sides of the polygon. The genotypes that are situated on the vertices of polygon are the winning genotypes (Yan et al. 2000). In the present study, BPP-8 and Vengulra-7 were the winning genotypes in Bhubaneswar while Kanaka and Priyanka were the winning genotypes in Pilicode, Vengurla-4 in Jhargram and UN-50 in Vridhachalam.

Ranking of genotypes as per ASV and YSI

The genotypes were ranked for their stable performance across the environments using additive main effect and multiplicative interaction (AMMI) stability value (ASV) and yield stability index (YSI) separately (Table 6). Low ASV scores denote the most stable genotypes and hence ranks were assigned accordingly. K-22-1 ranked first according to ASV rankings followed by Bhubaneswar-1. According to YSI, genotypes with lesser YSI values are stable for yield. On the basis of YSI values, Bhubaneswar-1 ranked first and the second rank was shared by K-22-1 and BPP-8. It is interesting to note here that K-22-1 ranked first as per ASV and ranked second as per YSI.

Table 6
Ranking of genotypes as per ASV and YSI for cumulative nut yield

S.No.	Genotype	Mean	Rank (A)	ASV Score	ASV Rank (B)	YSI (A + B)	YSI Rank
1	BPP-8	23.26	3	9.38	9	12	2
2	Bhubaneswar-1	20.13	5	2.81	2	7	1
3	Madakkathara-1	14.78	16	4.19	4	20	6
4	Madakkathara-2	17.58	10	15.79	15	25	9
5	K-22-1	15.99	11	1.08	1	12	2
6	Dhana	15.65	13	10.42	10	23	9
7	Kanaka	24.70	1	29.48	17	18	5
8	Priyanka	24.00	2	37.32	18	20	6
9	Amrutha	17.65	9	12.07	12	21	7
10	Vengurla-4	17.85	8	14.02	13	21	7
11	Vengurla-7	21.27	4	17.64	16	20	6
12	VRI-3	15.59	14	9.06	8	22	8
13	NRCC Sel-2	15.01	15	10.58	11	26	11
14	Ullal-3	15.75	12	4.64	5	17	4
15	Ullal-4	18.60	7	6.97	7	14	3
16	UN-50	12.74	18	3.85	3	21	7
17	Goa-1	14.61	17	6.74	6	23	9
18	Bhaskara	20.08	6	14.51	14	20	6

Discussion

In our study, the combined AMMI analysis showed that G×E interaction was highly significant for cumulative nut yield. This indicates the differences in adaptation by the genotypes or the effect of environment on the performance of genotypes and signify the necessity to identify environment specific genotypes. The variability captured by IPCA 1 and IPCA 2 was about 95% in the G× E interaction for nut yield and it demonstrated the adequacy of the AMMI II model. These results are corroborated with report of 99.1% for the first two IPCAs in cashew in Nigeria (Aliyu et al., 2014). The extent of variation explained by G×E interaction was very high (77.22%) and underscored the importance of the study. The variation explained by genotype (16.18%) and environment (4.5%) was not so high. In Nigerian cashew breeding programme, Aliyu et al., (2014) reported variation explained by genotype of 53.53%, environment of 4.35% and G×E interaction of 24.69%. In mango which belongs to cashew family Anacardiaceae, the variation explained by genotypes, environments and G×E interaction were 6.95%, 37.78%, and 42.81% (Krishna et al., 2022). The differences in cashew and mango could be attributed to differences in the genotypes and the effect of environment.

The ranking of genotypes in each environment for the nine eight traits of 6th annual harvest (*Table 3 supplementary file*) indicated that their expression varied with environments. For instance, the maximum number of flowering laterals per m² in the variety Vridhachalam-3 in Bhubaneswar could be due to the conducive mean maximum (32°C) and minimum temperatures (22°C) prevailing in that location. Similarly, the maximum stem girth and tree spread in Vengurla-7 in Bhubaneswar could be attributed to good soil fertility. The maximum sex ratio in Kanaka in Bhubaneswar might be due to ideal mean maximum (32°C) and minimum temperatures (22°C) in that region. The maximum tree height in Madakkathara-2 and nuts per panicle in Madakkathara-1 and nut weight in Priyanka in Pilicode could be due to very high average annual rainfall (3379 mm) and ideal mean maximum (33°C) and minimum temperature (23°C) prevalent in that location. The maximum shelling percentage in VRI-3 in Jhargram might be due to better drying of nuts due to high temperatures (46 °C) during post-harvest period in the hot and dry months of May and June. In light of the variable response of genotypes for different traits, it is worth to consider the suggestion given by Signor et al. (2001) and Mutwali et al. (2016) for analysis of environmental factors such as rainfall, sunlight, temperature and water holding capacity of soil during various phenological stages to understand the causative factors of G × E interaction. Many studies have showed the influence of environment on the growth, development and production of cashew trees (Aliyu et al. 2014; Bello et al. 2016, Bellow et al. 2019; Sethi et al. 2020) and other crops (Dhillon et al. 2009; Anley et al., 2013; Kumar et al. 2014).

In cashew, the cumulative nut yield of six years (six annual harvests) i.e., from 3rd year (starting year of fruiting) to 8th year of planting is considered for evaluating the yield performance of genotypes. Thus, stability of genotypes was assessed for cumulative nut yield of six years. In light of the better discrimination by the environment Pilicode for cumulative yield, it becomes the choice of environments for testing the genotypes. The assessment of stability based on ASV revealed that K-22-1 was the most stable genotype followed by Bhubaneswar-1 across four environments. It is said that stability only for yield performance does not merit selection as a constantly low yielding genotype can still be stable (Yan and Tinker 2006). Besides, it is said that the most stable genotype based on ASV does not show the best yield performance in some cases (Oliveira and Godoy 2006). It is true in the present study as the yield of K-22-1 is much lower than Bhubaneswar-1, yet it is found stable genotype based on ASV. Thus, it is imperative to ponder index YSI proposed by Farshadfar et al. (2011) which combines both high yield and stability of genotypes across environments. Consequently, YSI was estimated for cashew genotypes and it uncovered Bhubaneswar-1 as the most stable and high yielding genotype followed by BPP-8 and K-22-1, both of which shared second rank.

Conclusion

The findings of this study in cashew revealed the significant genotype by environment interaction for most of the yield associated traits, annual and cumulative nut yields. The study concludes that genotypes Bhubaneswar-1, BPP-8 and K-22-1 are stable and high yielding for cumulative nut yield and hence may be suggested for cultivation in west and east coast regions of India.

Materials and Methods

Study Environments

The trials were conducted in four environments (Fig. 1) which are the cashew research centers under All India Coordinated Research Project (AICRP) on Cashew in India viz., 1) Regional Agricultural Research Station, Pilicode (KAU), 2) Regional Research Station, Vridhachalam (TNAU), 3) Bhubaneswar (OUAT) and 4) Regional Research Station, Jhargram (BCKV).

The Pilicode station is geographically located at 13°N latitude and 75°E longitude at an elevation of 15m above MSL. It receives 3379 mm of average annual rainfall and rainy season is from June to October. The mean maximum and minimum temperature of the location is 33°C and 23°C respectively. The soil are laterite.

The Vridhachalam station lies at 11.30°N latitude and 79.26°E longitudes and at an altitude of 42.67 m above MSL. The nearest sea coast is within 50 km distance. It receives rains from both south-west (June-September) and north-east (October-December) monsoons and the mean annual

rainfall is 1020 mm. The mean maximum and minimum temperature of the location is 42°C and 19°C respectively. The soils are red laterite and sandy.

Jhargram is located at 22.45° N 86.98° E. It has an average elevation of 81 metres (265 feet). The weather is extremely humid and tropical. Temperatures can reach as high as 46 °C in the hot and dry months of May and June but can plummet to 4°C in the chilly nights of December and January. This location receives rains during June to October with an average annual rainfall of 1400 mm. Soils are sandy loam.

The Bhubaneswar is at 20°15' North latitude and 82°52' East longitude and is at an elevation of 25.5 m above MSL. It receives rains during June to October with average annual rainfall of 1640 mm. The mean maximum and minimum temperature of the location is 32°C and 22°C respectively. Soils are sandy loam.

Experimental material

Eighteen cashew genotypes viz., Amrutha, Bhaskara, Bhubaneswar-1, BPP-8, Dhana, Goa-1, K-22-1, Kanaka, Madakkathara-1, Madakkathara-2, NRCC Sel-2, Priyanka, Ullal-3, Ullal-4, UN-50, Vengurla-4, Vengurla-7, VRI-3 formed the experimental material for the study. The list of genotypes and their source is presented in the Table 1 (Salam and Bhaskara Rao, 2001).

Experimental design and layout

The experiment was designated as Multi-Location Trial-V (MLT-V) and started in the year 2008 in three locations Bhubaneswar, Pilicode, Vridhachalam and in the year 2010 at Jhargram location. The genotypes were planted at 7m x 7m spacing in randomized block design (RBD) with two replications. There were three trees / genotype in each replication. Recommended horticultural practices and plant protection measures for were adopted for raising the plants and protecting the plantation.

Data collection

The data was collected for nut yield for six annual harvests from 3rd year after planting as per the methodology described in the experimental manual on cashew by the National Research Center for Cashew (NRCC, 2005). The height of tree was measured using marked bamboo pole / PVC pipe from the ground to the tip of the main branch in meters. The circumference of the trunk or main stem at the collar region (15 cm above ground level) was measured using measuring tape in centimeters. The canopy spread in east-west direction and north-south direction was measured using measuring tape and average of the two directions was expressed as tree spread in metre. The number of flowering laterals were counted from one square metre area of canopy in four directions using frame of one square metre bamboo poles and the mean of four directions was arrived. For sex ratio, three panicles were selected from the observational tree and they were tagged. The numbers of bisexual and male flowers appearing in each panicle were counted on alternate days and the counted flowers were removed. This was done till the end of flowering in those panicles. The total number of bisexual and male flowers in each panicle was obtained. The mean of bisexual flowers per panicle and mean of male flower per panicle was determined. The sex ratio was calculated as

$$\text{SexRatio} = \frac{\text{meanofbisexualflowres}}{\text{meanofmaleflowers}}$$

In case of nuts per panicle, matured nuts per panicle were counted in 20 panicles per tree in four directions and mean was taken. For nut weight, 50 raw nuts were sun dried for three days and weight was taken in grams. The mean weight of nut was calculated as

$$\text{Nutweight} = \frac{\text{weightof50nuts}}{\text{numberofnuts}}$$

For shelling percentage, 50 raw nuts were weighed and weight was taken in grams. These nuts were shelled using shelling machine. Weight of kernel with testa and weight of shells obtained after shelling were recorded separately. The shelling percentage was calculated as

$$\text{Shellingpercentage} = \frac{\text{weightofkernelswithtesta}}{\text{weightofnut}} \times 100$$

For annual nut yield, matured nuts were harvested separately from three trees per genotype in each replication during the entire period of fruiting season from February-May every year. The harvested nuts from each tree were sun dried for three days and weighed for each genotype separately and expressed as nut yield / tree in kg. Likewise nut yield was collected for six years in each environment. The nut yield of six years was added to obtain cumulative nut yield / tree in kg.

Statistical analysis

The data of 6th annual harvest (considered as year of attaining stable yield by the cashew tree) for nine traits and the data of cumulative nut yield of six years from the four environments was subjected for AMMI (additive main effect and multiplicative interaction) and GGE (genotype and genotype by environment) bi-plot analyses using the software GENSTAT-18.1 version by VSN International Ltd. (www.vsni.co.uk/software/genstat). The additive main effects of genotypes and environments were fitted by univariate ANOVA and $G \times E$ interaction was fitted by principal component analysis based on the AMMI II model. The graphical representations of GGE biplots were drawn using GEA-R software (Pacheco et al.2015). Stability of genotypes was assessed using the following two methods.

AMMI stability value (ASV)

$$\text{ASV} = \sqrt{\left\{ \frac{\text{IPCA1SS}}{\text{IPCA2SS}} \right\} \times (\text{IPCA1score})^2 + (\text{IPCA2score})^2}$$

Where, IPCA1 SS and IPCA2 SS are sum of squares corresponding to first two IPCA's. Smaller ASV values denote the greater stability of genotypes across environments (Purchase et al., 2000).

Yield stability index (YSI)

This method enables simultaneous selection of genotype for high yield as well as stability, as it takes into account both yield and stability in a single measure (Farshadfar et al., 2011). YSI was estimated using the following formula.

$\text{YSI} = \text{RASV} + \text{RY}$, Where, RASV is the rank of the genotypes based on the ASV and RY is the rank of the genotypes based on yield across environments

Declarations

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Conflict of interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available within the article [and/or] its supplementary materials.

Author Contribution

Eradasappa E.- Conceptualized the idea, compiled and formatted the data for analysis, wrote the main manuscript. Mohana G.S. - Coordinated and helped in gathering data from different research centers. Poduval, M. Sethi, K. Aneesa Rani, M. S. Lourdusamy, I. K. Velmurugan, S. Manjusha, M.- conducted the investigation and collected the data from the experiments. Bhat, M.G. and Raviprasad, T.N. - Monitored the trials at different centers as Project Coordinator and In-charge of AICRP on cashew respectively. Anilkumar, C.- Carried out the statistical analysis of data and prepared the graphs. All the authors reviewed the manuscript.

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Supplementary File

Supplementary File (Table 3) is not available with this version.

Figures

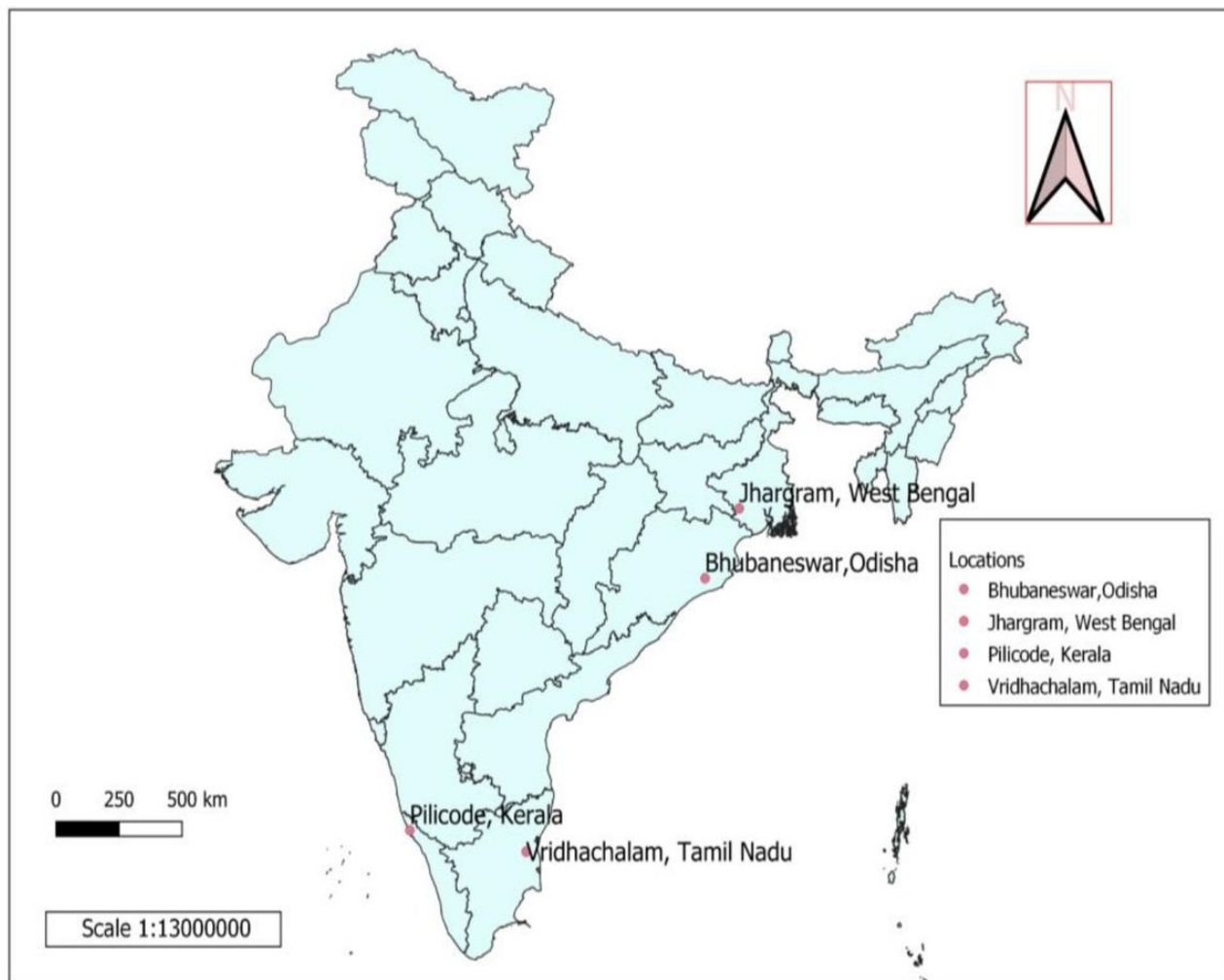
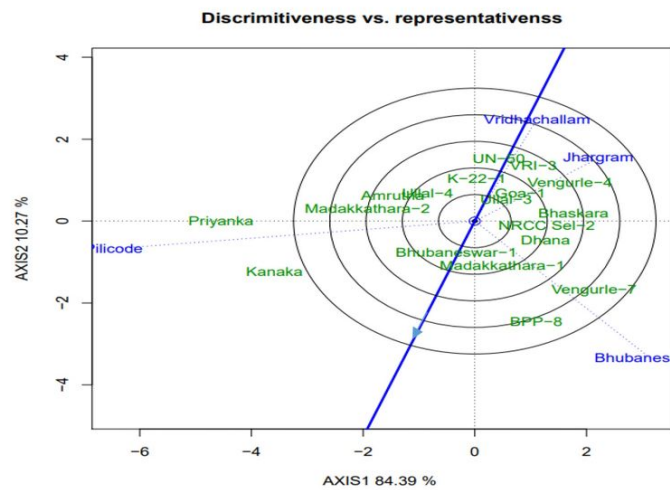
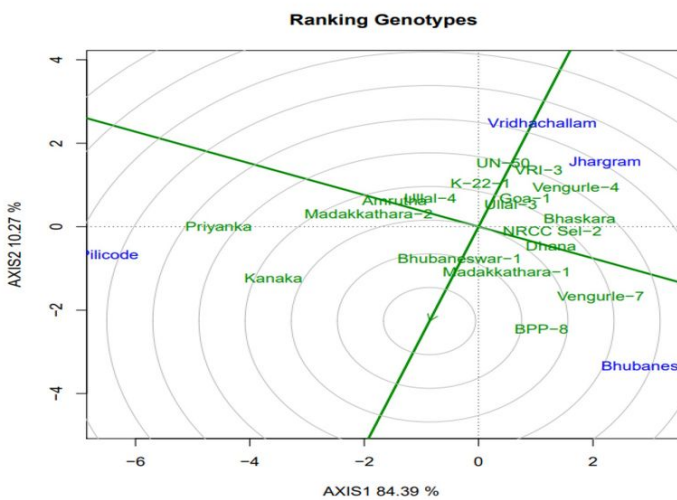


Figure 1

India map showing the 4 experimental locations (environments) of the study.



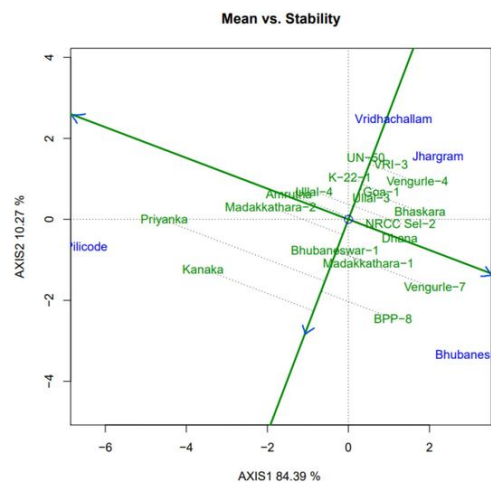
a



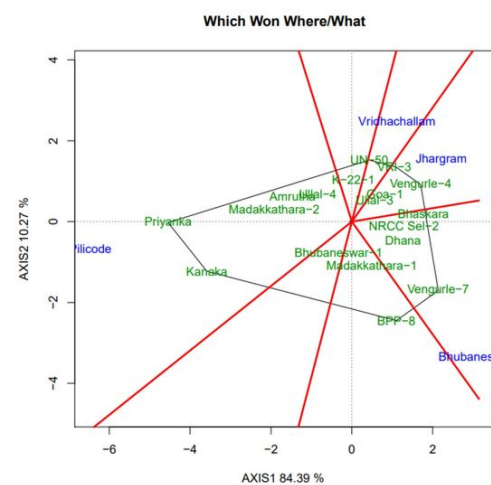
b

Figure 2

GGE bi-plots of cashew genotypes displaying a-Discriminative vs. representativeness b- ranking of genotypes (ideal genotype)



a



b

Figure 3

GGE bi-plots of cashew genotypes showing a- mean vs. stability b- 'which-won-where' for cumulative nut yield per tree.