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Original Research Paper

Evaluation of farmers' varieties of cardamom (*Elettaria cardamomum* Maton): Assessing agronomic performance and adaptability in the central western ghats

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ABSTRACT

Cardamom (*Elettaria cardamomum* Maton), a monotypic genus in the family Zingiberaceae, is a significant spice crop cultivated primarily in India. In addition to improved varieties developed from research organizations, several farmer-identified varieties originating from the Southern Western Ghats are widely grown. In this study, nine farmer's varieties of cardamom along with a check variety were evaluated during 2020 to 2023 to assess their suitability for the region. Principal component analysis revealed that three principal components accounted for 78.17% of the overall variance. Key traits contributing to genetic diversity included essential oil content, plant height, panicle length, dry recovery, seed weight percentage, 100-seed weight, and 100-capsule weight. A two-dimensional GGE biplot, generated using the first two principal components, explained 85.92% and 11.14% of the genotype-environment interaction (GEI) for yield. Among the genotypes, Panikulangara Green Bold No. 1 emerged as the ideal variety with high yield potential. Multivariate analysis grouped the varieties into three categories: stable with high yield, less stable with high yield, and highly stable with low yield.

Keywords: central western ghats, farmers varieties, genotype×environment interaction, stability analysis, yield improvement

INTRODUCTION

Cardamom (*Elettaria cardamomum* Maton), the only species in the genus *Elettaria* (family Zingiberaceae), is a perennial rhizomatous spice crop native to the moist evergreen forests of the Western Ghats, India. It is Renowned for its pleasant aroma and flavour, it is popularly known as the 'Queen of Spices' (Ravindran, 2002). Major cardamom-producing countries include Guatemala, India, Tanzania, Sri Lanka, Laos, Vietnam and Papua New Guinea. In India, cardamom was cultivated over 70,410 ha with a production of 20,696 tonnes during 2024-25, mainly in Kerala, Karnataka and Tamil Nadu (www.indian-spices.com).

Based on adaptability and panicle growth habit, cardamom accessions are classified into Malabar, Mysore and *Vazhukka* types. Malabar types are adapted to lower elevations (600-1000 m MSL), whereas Mysore and *Vazhukka* types perform better at higher elevations (900-1200 m MSL) (Madhusoodanan et al., 2002). Despite these classifications, accessions from all three groups often cluster together due to shared ancestry (Prasath & Venugopal, 2004). In addition to varieties released by research institutions, several farmer-developed varieties have been recognized through the PPVFRA and the National Innovation Foundation.

Genetic diversity among cardamom genotypes can be effectively assessed using principal component analysis, which identifies patterns in multidimensional datasets (Brown-Guedira et al., 2000). As cardamom is a perennial crop, selecting stable, high-performing varieties is essential because varietal replacement is infrequent. Although multi-environment trials are ideal for studying genotype×environment interactions, long-term evaluation across years is often more practical and reliable in perennial crops (Yan & Rajcan, 2003). Stability analyses such as AMMI and biplots are widely used to evaluate genotype performance across environments (Mahadevaiah et al., 2021), and farmers generally prefer varieties with consistent performance over years (Spoorthi et al., 2021).

Most farmer-developed varieties belong to the Mysore or *Vazhukka* types and originated in the Southern Western Ghats (Prasath et al., 2024; Korikanthimath

Table 1 : Estimates of correlation coefficients among different traits in farmers varieties of cardamom

Trait	Plant height (cm)	No. of tillers	No. of bearing tillers	No. of panicles	Panicle Penicle length (cm)	Fresh weight/ plant (g)	Dry recovery (%)	Dry weight/ plant (g)
Plant height (cm)	1							
No. of tillers	0.754**	1						
No. of bearing tillers	0.389	0.789**	1					
No. of panicles	0.468	0.822**	0.904***	1				
Panicle length (cm)	0.526	0.694*	0.577	0.740**	1			
Fresh weight per plant (g)	0.486	0.779**	0.833**	0.849**	0.652*	1		
Dry recovery (%)	-0.436	-0.13	-0.012	0.015	-0.033	-0.21	1	
Dry weight per plant (g)	0.437	0.784**	0.854**	0.880**	0.673*	0.985***	-0.056	1

** correlation is significant at 0.01 level; *correlation is significant at 0.05 level

et al., 2024). Their adaptability to the climatically distinct Central Western Ghats of Karnataka remains inadequately understood. Therefore, the present study evaluated the suitability and stability of popular farmer-developed varieties under the central western ghats to identify genotypes best suited for the region and support future breeding efforts.

MATERIALS AND METHODS

The experiment was conducted at ICAR–Indian Institute of Spices Research, Regional Station, Appangala, Madikeri, Karnataka (12° 26° N, 75° 45° E). Nine farmer-developed cardamom varieties, namely Thiruthali, Wonder Cardamom, *Njallani* Green Gold, Panikulangara Green Bold No. 1, Elarajan, Pappalu, Arjun, Pachaikkai and PNS Vaigai, along with the check variety Appangala-1 (Supplementary Table), were evaluated during 2020 to 2023, in a randomized block design with three replications, 12 plants per replication, at 3 × 3 m spacing. The crop was maintained following the recommended package of practices (IISR, 2022).

Data on 12 traits, including plant height, bearing tillers, panicles per plant, panicle length, fresh and dry capsule yield, essential oil, seeds per capsule, seed weight (%), 100-capsule weight and 100-seed weight, were recorded over three years. Morphological traits were recorded after flowering, while quality traits were estimated from matured and cured capsules. Dry recovery was calculated from fresh and dry capsule weights and essential oil was estimated by the modified Clevenger hydro-distillation method (ASTA, 1968).

Principal component analysis was performed using the GRAPES statistical package (Gopinath et al., 2020). Yield stability and genotype × environment interaction was analysed using GGE biplot (Yan, 2001) and AMMI analysis (Gauch, 2013), with graphical outputs generated in RStudio (RStudio, 2014).

Leaf blight resistance was assessed through visual scoring and the percentage disease index (PDI) was calculated from 8–12 inner tillers per clump to classify genotypes from highly resistant to highly susceptible (Praveena et al., 2013). Thrips and capsule borer damage were evaluated during 2021–2022 using random 50 g dried capsule samples from each replication and damage was expressed as the percentage of infested capsules.

RESULTS AND DISCUSSION

Correlation coefficients of characters attributed to yield per plant were estimated (Table 1). Yield per plant showed significant positive correlations with number of tillers, bearing tillers, panicles, panicle length and fresh weight per plant, indicating their importance as selection criteria for yield improvement. Similar positive associations were reported by Senthil Kumar et al. (2018) and Backiyarani et al. (2002) in cardamom.

Principal component analysis

In the present study, the first three principal components (eigen value >1) explained 78.17% of the total variation, with individual contributions of 53.90%, 12.87% and 11.40%, respectively (Table 2). PC1 was positively associated with essential oil, PC2 with plant height, panicle length, dry recovery and seed weight percentage, while PC3 showed a negative association with 100-seed weight and 100-capsule weight. These traits contributed most to genetic diversity, consistent with Herrera-González et al. (2024).

Table 2 : Eigen values, percent values and principal component analysis on yield of cardamom

Trait	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9
Eigen values	6.46	1.54	1.36	0.99	0.77	0.41	0.28	0.11	0.02
Variation (%)	53.90	12.87	11.40	8.26	6.49	3.45	2.40	0.98	0.21
Cumulative variation (%)	53.90	66.77	78.17	86.44	92.93	96.39	98.80	99.78	100.00
		Eigen vector							
Plant height (cm)	-0.27	0.35	0.15						
Number of bearing tillers	-0.34	-0.16	-0.16						
Number of panicles	-0.36	0.07	-0.05						
Panicle length (cm)	-0.33	0.26	-0.04						
Fresh weight (g/plant)	-0.37	0.16	-0.03						
Dry weight (g/plant)	-0.37	0.10	0.01						
Dry recovery (%)	-0.21	-0.44	0.36						
Essential oil (%)	0.19	-0.16	0.21						
Number of seeds per capsule	-0.15	-0.40	0.28						
Seed weight (%)	-0.30	-0.30	0.34						
100 capsule weight (g)	-0.28	-0.10	-0.42						
100 seed weight (g)	-0.01	-0.49	-0.62						

PCA biplot

Principal component analysis (PCA) explained 53.9% (Dim1) and 12.9% (Dim2) of the total variation (Fig. 1). Two distinct genotype clusters were observed. Wonder Cardamom, Green Gold and Appangala-1 showed strong positive influence on Dim1, whereas Pappalu, Panikulangara and Thiruthali showed strong negative influence. Similar applications of PCA were reported by Herrera-González et al. (2024) and Akshitha et al. (2020) in cardamom and ginger, respectively.

AMMI analysis of variance

The AMMI analysis with ANOVA revealed significant effects of years, genotypes and G×E interaction on cardamom yield (Table 3), indicating strong environmental influence and differential genotype performance across years. PC1 explained 73.7% and PC2 26.3% of the total variance, together accounting for 100% of the variability. These results validate the effectiveness of AMMI for evaluating yield performance and stability, highlighting the importance of selecting high-yielding, stable and adaptable genotypes for breeding programs under diverse environmental conditions.

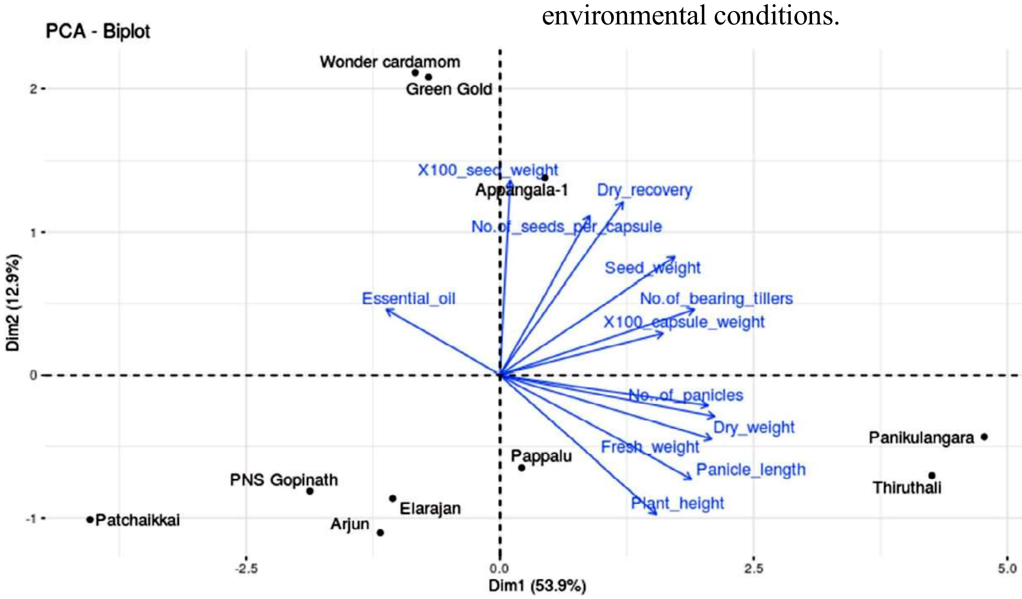

Fig. 1 : Principal component analysis biplot for PC 1 and PC 2

Table 3 : AMMI analysis of variance for yield in cardamom

Source	df	SS	MS	F value	P value	Proportion	Cumulative (%)
Years	2	106937.9	53468.97	45.92774	0.000231		
Replication	6	6985.18	1164.19	0.851979	0.535943		
Genotype	9	332512.4	36945.82	27.03754	0.00		
Interactions	18	233281.1	12960.06	9.484381	0.00		
PC1	10	172019.3	17201.93	12.59		73.7	73.7
PC2	8	61261.81	7657.72	5.6		26.3	100
Residuals	54	73789.04	1366.46				
Error	107	986786.8	9222.30				

AMMI biplot

The AMMI biplot illustrated yield performance and genotype × environment (G×E) interactions of cardamom genotypes across 2020, 2021 and 2022 (Fig. 2). Panikulangara Green Bold No. 1 recorded the highest yield and showed specific adaptation to the 2021 environment. Thiruthali exhibited the largest interaction effect, indicating superior performance in 2022 but only average stability. Pachaikkai, Green Gold, Arjun and PNS Vaigai clustered near the origin, indicating average performance and broad stability. Genotypes with PC1 scores close to zero are considered widely adapted, whereas those distant from the origin are specifically adapted to particular environments (Murphy et al., 2009). The year 2021 was the most favourable environment, while 2020 and 2022 were less variable. These findings highlight the importance of selecting genotypes combining high yield and stability for sustainable cardamom improvement.

GGE biplot

The GGE biplot effectively illustrated genotype×environment (G×E) interactions and genotype performance across three years (Yan & Tinker, 2016). PC1 and PC2 explained 85.92% and 11.14% of the total variation, respectively (Fig. 3). Panikulangara Green Bold No. 1 was the highest-yielding genotype, showing specific adaptation to 2020 and 2021, while Thiruthali was best adapted to 2022. Elarajan, Green Gold and Appangala-1 exhibited intermediate performance with moderate stability. The 2020 and 2021 environments were more favourable than 2022, highlighting the importance of G×E

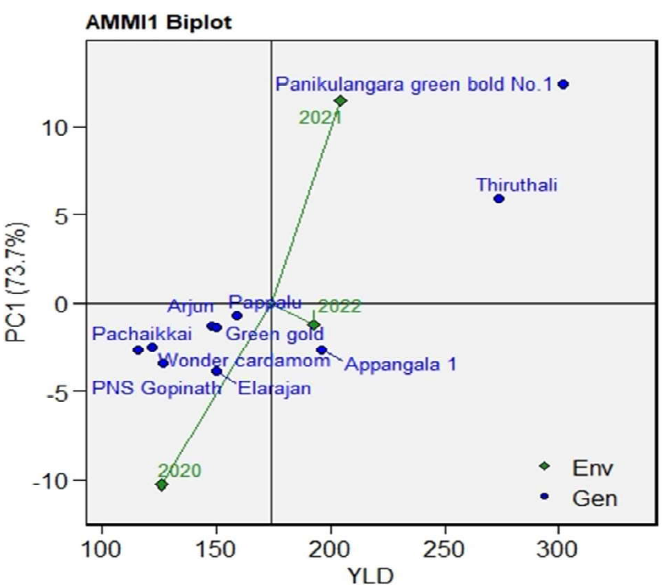

Fig. 2 : AMMI Biplot representing yield and PC 1

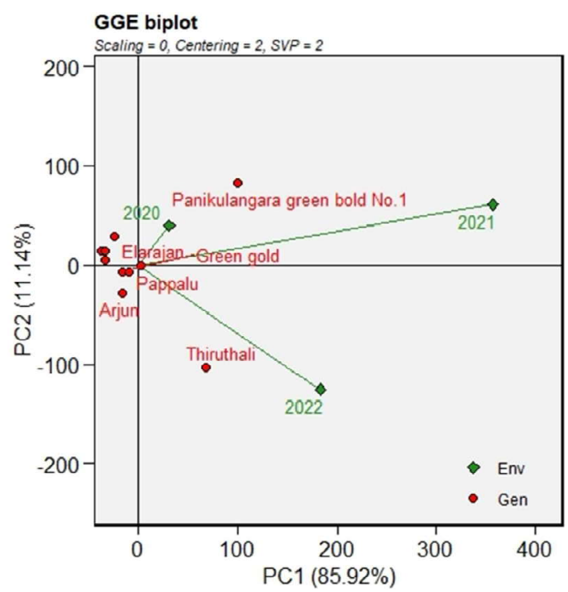

Fig 3 : GGE biplot representing the performance and stability of cardamom genotypes across three years analysis for selecting stable, high-yielding cardamom genotypes.

Which-won-where

The "which-won-where" GGE biplot identified the best-performing cardamom varieties across three years (Fig. 4). Six sectors were formed, of which two represented distinct mega-environments. The 2020 and 2021 environments grouped together, with Panikulangara Green Bold No. 1 as the winning genotype, indicating superior adaptability and yield under these conditions. The 2022 environment formed a separate mega-environment, where Thiruthali was the highest-yielding genotype. Wonder Cardamom and Green Gold exhibited moderate performance across environments, while Elarajan and Arjun, located near the biplot origin, showed stable but average yields. The distinct sectors confirmed significant genotype × environment (G×E) interactions, indicating that Panikulangara Green Bold No. 1 and Thiruthali are best suited to environments similar to 2020–2021 and 2022, respectively, whereas stable varieties are suitable for variable conditions. Similar year-specific genotype performance has been reported in black pepper by Shivakumar et al. (2024).

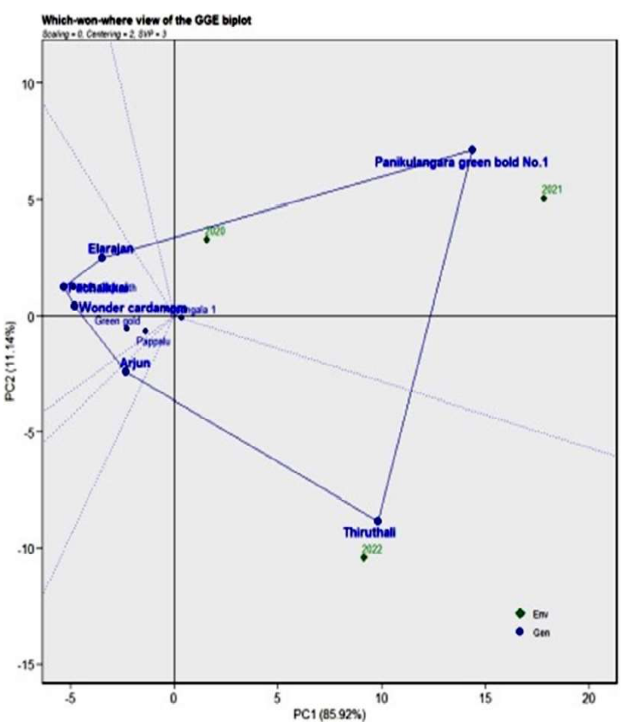

Fig. 4 : GGE biplot depicting which genotype performed better in which environment for yield of cardamom

Mean v/s stability of cardamom varieties across multiple environments/years

The "mean vs. stability" GGE biplot evaluated yield and stability of ten cardamom varieties across three years (Fig. 5). The average environment coordinate (AEC) consists of the AEC abscissa and ordinate, with the arrow indicating increasing mean yield (Khan et al., 2021). Panikulangara Green Bold No. 1 recorded the highest mean yield, followed by Thiruthali, whereas Elarajan, Wonder Cardamom and Arjun had lower mean yields. Stability was indicated by proximity to the AEC abscissa; Appangala-1 was the most stable, while Thiruthali, despite its high yield, was the least stable. The 2021 environment favoured Panikulangara Green Bold No. 1, whereas 2022 favoured Thiruthali, confirming significant genotype × environment interactions. Similar stability analysis has been reported in turmeric by Aarthi et al. (2020). Genotypes nearest the concentric rings are considered ideal and projections from the AEC abscissa indicate stability (Oladosu et al., 2017).

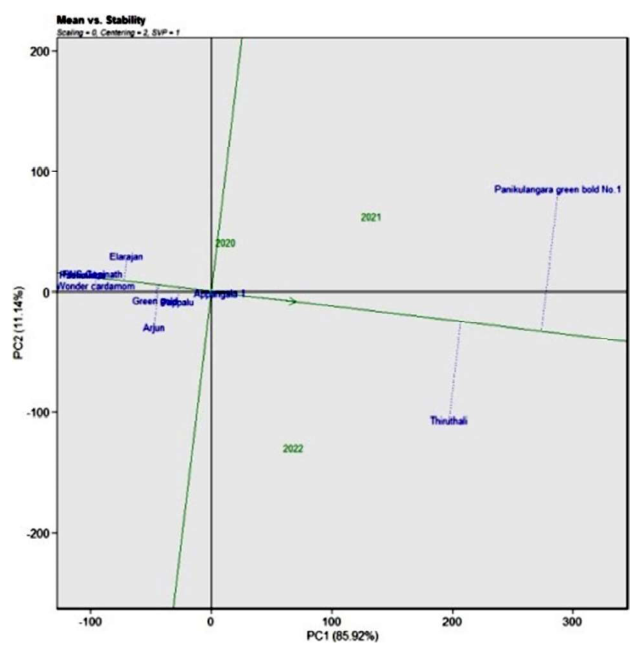

Fig. 5 : GGE biplot depicting Mean v/s stability of cardamom varieties

Genotype ranking

The GGE biplot (ranking genotypes) assessed the yield performance and stability of cardamom genotypes across three years (Fig. 6). Genotypes located closest to the innermost concentric circle are considered ideal, while those nearest the inner circle are preferred when no genotype occupies the centre (Oladosu et al., 2017). Panikulangara Green Bold No. 1, positioned nearest the innermost circle, was identified as the ideal genotype with high yield and broad adaptability. In contrast, Thiruthali exhibited superior performance under the 2022 environment but showed lower stability across years. These findings emphasize the importance of selecting genotypes with both high yield and stability. Similar observations have been reported in black pepper, where OPKM followed by IISR Thevam were identified as ideal genotypes (Shivakumar et al., 2024) and in rice and Bambara groundnut by Oladosu et al. (2017) and Khan et al. (2021), respectively.

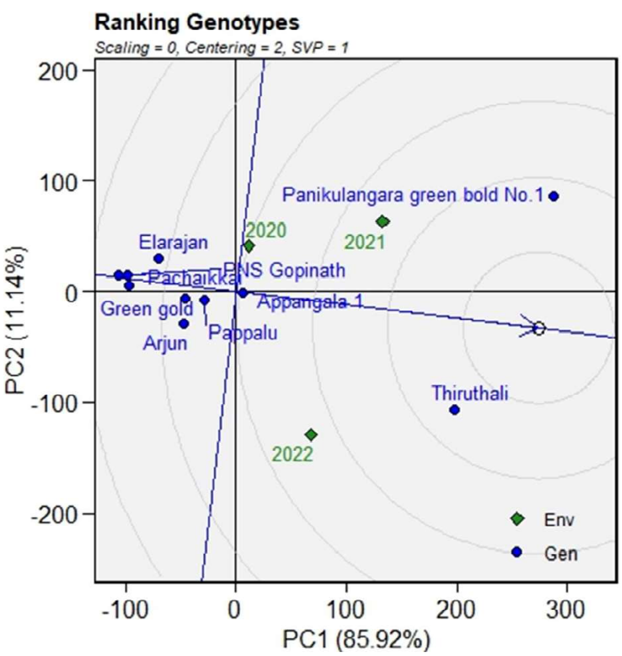

Fig. 6 : GGE biplot 'genotype ranking' pattern for genotype comparison

Discriminativeness and representativeness

The GGE biplot for discriminativeness and representativeness evaluated the suitability of test environments for genotype assessment (Fig. 7). The 2021 environment had the longest vector and the smallest angle with the average environment axis, indicating that it was the most discriminative and representative environment for evaluating yield and adaptability. In contrast, 2020 and 2022 had shorter vectors, indicating lower discriminative ability and representativeness (Oladosu et al., 2017). Panikulangara Green Bold No. 1 was the most suitable genotype for stable, high yield under representative conditions, whereas Thiruthali showed specific adaptation to 2022. These findings emphasize the importance of representative environments for reliable genotype evaluation and selection.

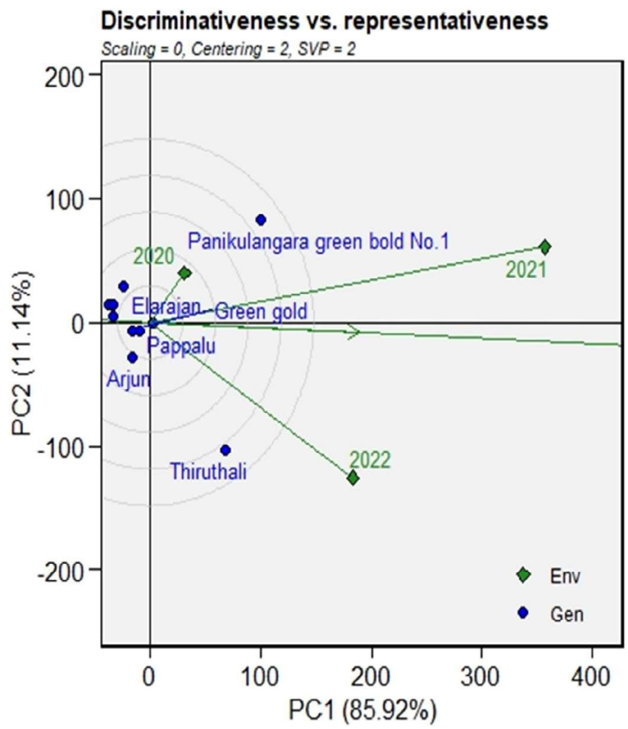

Fig. 7 : GGE biplot 'Discriminativeness vs. representativeness' pattern

Varietal reaction to pest and diseases

The pooled disease incidence (PDI) among the tested varieties ranged from 16.11% to 22.21%, with all varieties except Elarajan classified as resistant according to the standard disease rating scale (Table 4). Among the farmers' varieties, Thiruthali recorded the lowest PDI, followed by Wonder Cardamom and Panikulangara. Using the same scale, Praveena et al. (2013) reported six genotypes (IC-547222, IC-547223, IC-349645, IC-349649, IC-547158, and IC-349637) with moderate resistance under field conditions. Similarly, Sharon et al. (2020) identified 35 leaf blight-resistant genotypes based on PDI and the resistance classification scale.

Assessment of cardamom thrips and capsule borer damage in ten farmer-developed varieties during 2021 and 2022 revealed considerable variation in pest susceptibility (Table 5). In 2021, thrips infestation ranged from 3.45±1.17% to 44.66±8.70%. Pappalu recorded the highest damage, followed by PNS Vaigai, Arjun and Pachaikkai, whereas Thiruthali, Green Gold and Appangala-1 showed the lowest infestation,

Table 4 : Reaction of farmer's varieties to leaf blight

Varieties	Leaf blight PDI			
	2021-22	2022-23	Pooled	Category
V_1 - Thiruthali	15.56	16.67	16.11	Resistant
V_2 - Wonder cardamom	16.67	17.78	17.22	Resistant
V_3 - Green gold	22.22	22.22	22.23	Resistant
V_4 - Panikulangara	17.78	17.78	17.78	Resistant
V_5 - Appangala 1	21.11	17.78	19.44	Resistant
V_6 - Elarajan	22.22	22.22	22.21	Moderately resistant
V_7 - Pappalu	20.00	20.00	20.00	Resistant
V_8 - Arjun	20.00	20.00	20.00	Resistant
V_9 - Pachaikkai	20.00	20.00	20.00	Resistant
V_{10} - PNS Vaigai	18.89	18.89	18.88	Resistant
CV (%)	14.41	17.33	7.72	
CD (5%)	NS	NS	1.96	

Table 5 : Reaction of farmer's varieties to thrips and capsule borer infestation

Varieties	Thrips damage (%) Mean±SE		Borer damage (%) Mean±SE	
	2021	2022	2021	2022
V_1 - Thiruthali	5.07±1.58	7.54±1.43	2.91±0.69	1.98±0.42
V_2 - Wonder cardamom	12.69±3.96	10.00±3.80	4.98±0.06	3.60±0.73
V_3 - Green gold	4.00±0.87	26.69±3.13	12.87±2.11	4.25±0.83
V_4 - Panikulangara	12.07±2.61	6.24±1.59	1.79±0.45	1.60±0.43
V_5 - Appangala 1	3.45±1.17	3.40±1.65	5.56±1.78	1.34±0.97
V_6 - Elarajan	17.06 ± 2.60	8.71 ± 2.22	9.92±1.07	3.29±0.81
V_7 - Pappalu	44.66 ± 8.70	26.32 ± 5.73	2.56±0.33	2.80±0.17
V_8 - Arjun	33.34 ± 10.33	31.55 ± 1.94	2.40±0.56	2.07±0.42
V_9 - Pachaikkai	29.37 ± 4.31	36.46 ± 5.49	1.23±0.25	3.89±1.18
V_{10} - PNS Vaigai	36.35±6.31	29.67±3.93	3.04±0.60	2.78±0.25

followed by Wonder Cardamom, Panikulangara and Elarajan. In 2022, thrips infestation declined (3.40±1.65% to 36.46±5.49%), with the highest damage in Arjun and Pachaikkai, followed by Green Gold (26.69±3.13%). Thiruthali, Wonder Cardamom and Pappalu (26.32±5.73%) exhibited moderate susceptibility. Cardamom thrips can damage 60-90% of capsules, causing 45-48% yield loss (Devasahayam et al., 2024).

Capsule borer infestation ranged from 1.23±0.25% to 12.87±2.11% in 2021, with Green Gold recording the highest damage, followed by Elarajan, while Appangala-1 and Wonder Cardamom showed moderate incidence. In 2022, infestation declined to 1.34±0.97%-4.25±0.83%, with Green Gold again recording the highest damage. Appangala-1 consistently showed the lowest incidence of both thrips and borer, indicating tolerance, whereas Pappalu, Arjun, Pachaikkai and PNS Vaigai were more susceptible to thrips than capsule borer, highlighting differential pest responses among varieties.

CONCLUSION

The present study demonstrated significant genetic variation and genotype×environment interactions among the evaluated farmers varieties in the Central western ghats which are developed in the Southern Western Ghats. Among the varieties, Panikulangara Green Bold No. 1 was found to be best suited for Central western ghats due to its best performance with high yield and adoptability. Thiruthali was found to be suitable for specific environment conditions and

Appangala 1 was a stable variety with less incidence of pest. Hence, from the study it can be concluded that Panikulangara Green Bold No. 1 is suitable for cultivation in Central western ghats.

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