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Dynamics of Essential Oil Yield Stability and Their Estimation by Additive Main Effects and Multiplicative Interaction Analysis in Rosemary Lines

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Abstract

To evaluate the stability of essential oil yield (EOY) in the ten rosemary lines, a study was conducted to investigate genotype × environment interactions (GEI) in the genetic stocks obtained from the National Gene Bank of CSIR-CIMAP, Lucknow, India. The AMMI stability model was used in this work to evaluate ten genotypes of rosemary in three distinct locations in the various climates of Indian states in order to find stable lines that can flourish in various climatic conditions. The genotype stability performance is also affected by the correlations. For each of the ten features, the AMMI analysis showed substantial ($p<0.05$) G×E interactions. The first interaction principal component (IPCA1) was significant for all traits, explaining a substantial portion of the interaction sum of squares. Stability assessment, based on IPCA1 scores (near zero) coupled with high mean performance, identified genotypes RM-5, RM-2, and RM-4 as stable and high-yielding across environments for essential oil content and key agronomic traits. These genotypes are recommended for extensive cultivation in the diverse agro-climatic zones of India.

Keywords

AMMI; aromatic shrub; genotype-by-environment interaction; mega-environments; *Rosmarinus officinalis*

1. Introduction

Rosemary is a perennial, evergreen, aromatic shrub belonging to the family Lamiaceae, known for the essential oil, which is rich in bioactive compounds such as 1,8-cineole, camphor, and α-pinene [1-4]. The essential oil is widely used in the food, pharmaceutical, perfumery, cosmetic, and essential oil industries due to its antimicrobial, antioxidant, and flavoring properties [5, 6].

India's diverse climatic conditions offer an opportunity for large-scale rosemary cultivation; however, variations in environmental conditions—such as temperature, rainfall, soil type, and altitude—can significantly influence both the essential oil yield and its chemical constituents [7-10]. Understanding the stability of the essential oil yield and chemical composition across locations is important for identifying ideal cultivation locations and optimizing the essential oil production practices for industrial applications. The recently developed rosemary variety ‘CIM-Hariyali’ has shown promising adaptability, high biomass production, and favorable essential oil content under Indian conditions [11-16]. However, the performance stability and the relationship between location-specific environmental factors and oil quality parameters remain largely unexplored in the different rosemary lines.

Multi-location evaluation combined with stability analysis and correlation studies can provide vital insights for recommending specific production zones and management strategies to farmers and industry stakeholders [4, 17-18]. Therefore, the objectives of this investigation were: (i) to quantify the magnitude of genotype, environment, and G×E interaction effects on EOY and chemical composition of ten rosemary lines; (ii) to apply the AMMI model to assess phenotypic stability and identify stable genotypes; and (iii) to recommend suitable genotypes for cultivation in specific or across the tested agro-climatic regions of India.

2. Materials and Methods

A study on *Rosmarinus officinalis* L. (Rosemary) was carried out on the ten genotypes for the two consecutive years (2021-22 and 2022-23) at the three locations: Humid subtropical location 1 (Lucknow), Tarai location 2 (Pantnagar), and Semi-arid tropical location 3 (Hyderabad) in India. The research site’s soil ranged from sandy to clay-loam (Table 1). The ten rosemary lines were evaluated across three locations in India: Lucknow (Uttar Pradesh), Pantnagar (Uttarakhand), and Hyderabad (Telangana) (Table 1). The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications at each location and spacing within and between plots = 45×45 cm. A basal dose of NPK (120:60:40 kg ha^{-1}) was applied at the time of planting using di-ammonium phosphate (DAP), urea, and muriate of potash (MOP). Two supplementary irrigations were provided. The aerial parts were harvested at 50% flowering stage, 9 months after planting.

Table 1. The weather conditions of three locations (Lucknow, Pantnagar, and Hyderabad) of India, and the genotypes, origin, and coordinates of rosemary lines

Parameters/Locations	Lucknow	Pantnagar	Hyderabad
Altitude	49 m above sea level	243.84m above sea level	542 m above sea level
Longitudes	80^{0} 28’ E	79^{0} 38’ E	78^{0} 8'E
Latitudes	26^{0} 18’ N	29^{0} 54’ N	17^{0} 35'N
Climate	Humid subtropical climate	Humid subtropical climate	Semi-arid tropical, mild winters, and dry summers
Average annual rainfall	915 mm	1350mm	740 mm
Soil	Loamy	Clay loam	Red sandy loam
Sand	58.07%	36.2%	71.9%
Silt	32.75%	46.0%	7.8 %
Clay	9.18%	17.8%	18.5%
pH (1:2.5)	7.3	7.1	8.27
Soil-to-solution ratio	1.10	1.4	1.25
Electrical conductivity (dSm^{-1})	0.22ds/m	0.75 ds/m	0.42 ds/m
Organic carbon	0.56%	1.23%	0.58%
Available Nitrogen	266.2 kg/ha	358.38 kg/ha	292.7 kg/ha
Available Phosphorus	23 kg/ha	64.72 kg/ha	11.23 kg/ha
Exchangeable Potassium	342 kg/ha	132.28 kg/ha	116.76 kg/ha
Relative humidity (%)	56.94%	72.83%	52.63%
Temp. Max.	25.75	36.00	39.2
Temp. Mini	16.94	5.00	11.1

Table 1 Continued

Genotypes	Origin	States of India	Coordinates
GEN 1	Ranikheat	Uttrakhand	29.6434° N, 79.4322° E
GEN 2	Dharmshala	Himachal	32.2190° N, 76.3234° E
GEN 3	Purara	Uttrakhand	29.95° North and 79.65° West
GEN 4	Purara	Uttrakhand	29.95° North and 79.65° West
GEN 5 (CIM Hariyali)	CSIR CIMAP, Lucknow	Uttar Pradesh	26.8467° N, 80.9462° E
GEN 6	Almora	Uttrakhand	29.5971°N 79.6591°E
GEN 7	Pant nagar	Uttrakhand	29.0222° N, 79.4908° E
GEN 8	CSIR CIMAP, Lucknow	Uttar Pradesh	26°53’40”N 80°58’56”E
GEN 9	CSIR CIMAP, Lucknow	Uttar Pradesh	26°53’40”N 80°58’56”E
GEN 10	CSIR CIMAP, Lucknow	Uttar Pradesh	26°53’40”N 80°58’56”E

2.1 Attributes

Data were recorded for two consecutive growing seasons (2021-22 and 2022-23). For each replication, five competitive plants were tagged, and the following ten traits were measured: X1= height of the plant (cm), X2=Branches/plant, X3= Fresh plant weight (g), X4= Dry plant weight (g), X5=Oil content (fresh %), X6=Oil content (shade dried%), X7=1,8-cineole (in fresh aerial parts), X8= Camphor (in fresh aerial parts), X9= 1,8-cineole (in dry aerial parts) and X10= Camphor (in dry aerial parts).

2.2 Distillation

The essential oil from the 200 g rosemary sample was extracted by hydro-distillation for 3 hours with 3 replications, using the Clevenger glass instrument [19]. The isolated essential oil was measured and treated with Na_2SO_4 and kept at 4°C for chemical investigation.

2.3 GC/GC-MS

The GC/GC-MS analysis was done by the method [20, 21].

2.4 Statistical analysis

A combined analysis of variance (ANOVA) was performed for each trait across three locations and two years, considering the following model: Y~ijk~ = μ + G~i~ + E~j~ + Y~k~ + GE~ij~ + GY~ik~ + EY~jk~ + ε~ijk~, where Y is the observed phenotype, μ is the grand mean, G is the genotype effect, E is the location effect, Y is the year effect, and ε is the residual error. Where appropriate, years were considered as part of the environment factor for stability analysis. For stability analysis, the Additive Main Effects and Multiplicative Interaction (AMMI) model was applied using the AMMISOFT software [22]. The AMMI model combines ANOVA for additive main effects (G and E) with principal component analysis (PCA) for the non-additive G×E interaction: Y~ij~ = μ + G~i~ + E~j~ + Σ~k~ (λ~k~ α~ik~ γ~jk~) + ε~ij~, where λ~k~ is the singular value for the k-th interaction principal component (IPC), and α~ik~ and γ~jk~ are the genotype and environment scores for IPC~k~. The number of significant IPC axes was determined using Gollob’s F-test. Genotype stability was assessed using the IPC1 score, with genotypes having scores near zero considered more stable across environments. The AMMI Stability Value (ASV) and Yield Stability Index (YSI) were also calculated (optional, but recommended). The correlation between trait means and their stability measures (IPC1 scores) was calculated using Pearson’s correlation coefficient.”

3. Results

The present study employed AMMI analysis to evaluate the essential oil yield and chemical composition of a dataset comprising ten lines from three different locations. Except for four traits—X3, X6, X8, and X9—all genotype (G) components were determined to be highly significant ($p<0.01$) at the level of significance ($p<0.05$).

The genotype × environment (G × E) component effects were moderately significant ($p<0.05$) for all traits except three traits, namely X1, X2, and X7, which were highly significant ($p<0.01$) in the ANOVA study. For the environment (E), all traits were highly significant except five traits, namely X1, X6, X8, X9, and X10, which were moderately significant ($P<0.05$). All traits were highly significant ($p < 0.01$) for treatment components (T), except X6, X8, and X9, which were moderately significant ($p < 0.05$). The three traits, namely X1, X2, and X7 for the IPCA 1, were highly significant ($p<0.01$); the remaining seven traits were moderately significant ($p<0.05$) (Table 2).

Table 2. Combined analysis of variance (ANOVA) for the ten traits of the rosemary

Source of variation	df	Traits mean sum of squares									
		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
TRT	29	146.88**	5.109**	490.273**	172.468**	0.144**	0.048*	16.522**	0.326*	2.934*	0.317**
GEN (G)	9	67.07**	6.283**	598.611*	205.939**	0.185**	0.052*	20.068**	0.387*	3.676*	0.387**
ENV (E)	2	29.02*	7.627**	742.558**	263.753**	0.181**	0.056*	16.343**	0.327*	3.192*	0.388*
G × E	18	199.89**	5.019**	474.740*	167.811*	0.136*	0.050*	16.213**	0.337*	2.957*	0.307*
IPC1	10	259.30**	5.656**	443.844*	169.311*	0.124*	0.053*	15.308**	0.335*	2.936*	0.294*
Residual	8	125.62**	4.224*	513.359*	165.937	0.152*	0.047	17.345**	0.296	2.665	0.324*
Error	60	7.04	1.998	232.389	80.591	0.062	0.024	7.009	0.184	1.599	0.140
Total	89										

Notes. GEN= genotype, ENV= environment (ENV 1=Lucknow, ENV 2=Pantnagar, Env 3= Hyderabad), TRT=treatment, X1=Plant height (cm), X2=Branches per plant, X3= Fresh Plant weight (g), X4= Dry plant weight (g), X5=Oil content (fresh %), X6=Oil content (shade dried%), X7=1,8-cineole (in fresh aerial parts), X8= Camphor (in fresh aerial parts), X9= 1,8-cineole (in dry aerial parts), X10= Camphor (in dry aerial parts).

4. Discussion

The analysis of the results revealed that the SS for GE signal and noise for plant height were 1.87 and 4.09 times higher than the main effects on the lines, respectively. Furthermore, a correlation (r) of -0.86 was found between the year mean and IPC1 score. The correlation (r) of 0.13 was found between the line mean and IPC1. For the X2 trait, the r between the GES and GEN were 0.96 and 0.64. The genotype mean × IPC1 = 0.21, and r = year means × IPC1 = .43. Table 3 displays correlations for additional qualities as well as patterns of SS, GEIS, and GEIN. Four winning lines (RM 4, 6, 8, and 9) for the characteristic X1 were also found for AMMI 1 and AMF in rosemary winners. However, two superior genotypes (RM 2 and RM 5; RM 1 and RM 4) were identified for traits X2 and X9, respectively. In mega-environments (M-e), the following seven features were identified as winner genotypes: X3 (RM 2, 5, and 6); X4 (RM 4, 5, and 6); X5 (RM 2, 5, and 10); X6, X7, and X10 (RM 2, 5, and 6); and X8 (RM 1, 4, and RM 9) [Tables 4-7; Figures 1-7 (a-d)].

Table 3. Elite stability parameters, estimated sums of squares for G × E signal, noise, and winners for the AMMI model in rosemary

Stability Parameters	Characters				
	X1	X2	X3	X4	X5
Genotypes never win	6	8	7	7	7
SS for GE-signal times GEN main effects	1.87	0.96	0.81	0.85	0.80
GE-noise times the GEN main effects	4.09	0.64	0.78	0.78	0.75
Switch from GEN to GEN at ENV	6-9	2-5	5-6	5-6	2-10
IPC1 score	-0.89	0.05	-1.71	-1.48	-0.25
‘r’ between GEN means and IPC1 scores	0.13	0.21	0.43	0.34	0.30
‘r’ between ENV means and IPC1 scores	-0.86	0.43	0.20	-0.09	0.82

Table 3 Continued

Stability parameters	X6	X7	X8	X9	X10
Genotypes never win	7	7	7	8	7
SS for GE-signal times GEN main effects	1.04	0.92	0.69	0.63	0.86
GE-noise times the GEN main effects	0.91	0.70	0.95	0.87	0.84
Switch from GEN to GEN at ENV	2-6	5-6	1-9	1-4	5-6
IPC1 score	-0.114	-0.60	-0.02	0.19	-0.33
'r' between GEN means and IPC1 scores	0.62	0.53	0.11	0.01	0.35
'r' between ENV means and IPC1 scores	0.93	0.62	0.99	0.98	-0.07

Notes. G × E = Genotype × environment; A = (AMMI: Additive Main effects and Multiplicative Interaction); IPC = Interaction principal component; GE/GEN-Genotype; ENV: Environment; SS = sum of squares; r = Correlation.

Table 4. Ranking for environment AMMI1 (Additive Main effects and Multiplicative Interaction) and AMMIF for AMMI model Family for the ten traits of rosemary

Environment/Traits		AMMI I Ranks					AMMI F Ranks				
Plant height (cm)	Ratio	1	2	3	4	5	1	2	3	4	5
ENV1	1.034	6	2	9	1	8	8	9	6	5	3
ENV2	1.131	6	1	2	9	8	6	1	2	10	9
ENV3	1.000	9	4	5	10	7	4	9	10	5	7
Branches per plant											
ENV1	1.108	2	9	5	6	1	2	5	9	8	4
ENV2	1.269	2	9	5	6	1	2	6	9	7	1
ENV3	1.000	5	10	9	4	6	5	10	4	9	6
Fresh Plant weight (g)											
ENV1	1.000	5	2	9	4	10	2	5	9	8	4
ENV2	1.189	6	2	1	9	7	6	2	1	9	7
ENV3	1.000	5	2	9	4	10	5	10	4	9	6
Dry plant weight (g)											
ENV1	1.000	5	9	2	4	8	5	2	8	9	4
ENV2	1.179	6	1	2	9	8	6	1	2	9	8
ENV3	1.000	5	9	4	2	10	4	9	10	5	2
Oil content (fresh %)											
ENV1	1.000	2	9	5	1	8	2	5	9	8	4
ENV2	1.000	2	5	9	6	1	2	6	9	1	7
ENV3	1.519	10	5	6	4	9	5	10	4	9	6
Oil content (shade dried%)											
ENV1	1.000	2	5	9	8	6	2	5	9	8	3
ENV2	1.136	6	10	2	5	9	2	6	7	1	9
ENV3	1.141	6	10	2	5	9	5	10	6	4	9
1,8-cineole (in fresh aerial parts)											
ENV1	1.000	5	2	9	8	4	2	5	9	8	4

Table 4 Continued

Environment/Traits	AMMI I Ranks						AMMI F Ranks				
ENV2	1.207	6	2	9	1	7	6	2	1	9	7
ENV3	1.000	5	2	9	6	4	5	10	4	9	6
				Camphor (in fresh aerial parts)							
ENV1	1.013	1	8	4	5	2	1	4	8	2	5
ENV2	1.009	1	8	4	5	2	1	6	5	8	9
ENV3	1.002	9	4	2	5	10	4	9	2	10	5
				1,8-cineole (in dry aerial parts)							
ENV1	1.034	1	8	5	4	2	1	4	8	2	5
ENV2	1.046	1	8	5	2	4	1	6	5	8	9
ENV3	1.000	4	9	2	5	10	4	9	2	10	5
				Camphor (in dry aerial parts)							
ENV1	1.00	5	9	2	4	10	2	5	9	8	4
ENV2	1.02	6	2	1	9	5	6	2	1	9	5
ENV3	1.00	5	9	2	4	10	5	10	4	9	6

Notes. AMMI1 (Additive Main effects and Multiplicative Interaction); ENV = year/environment.

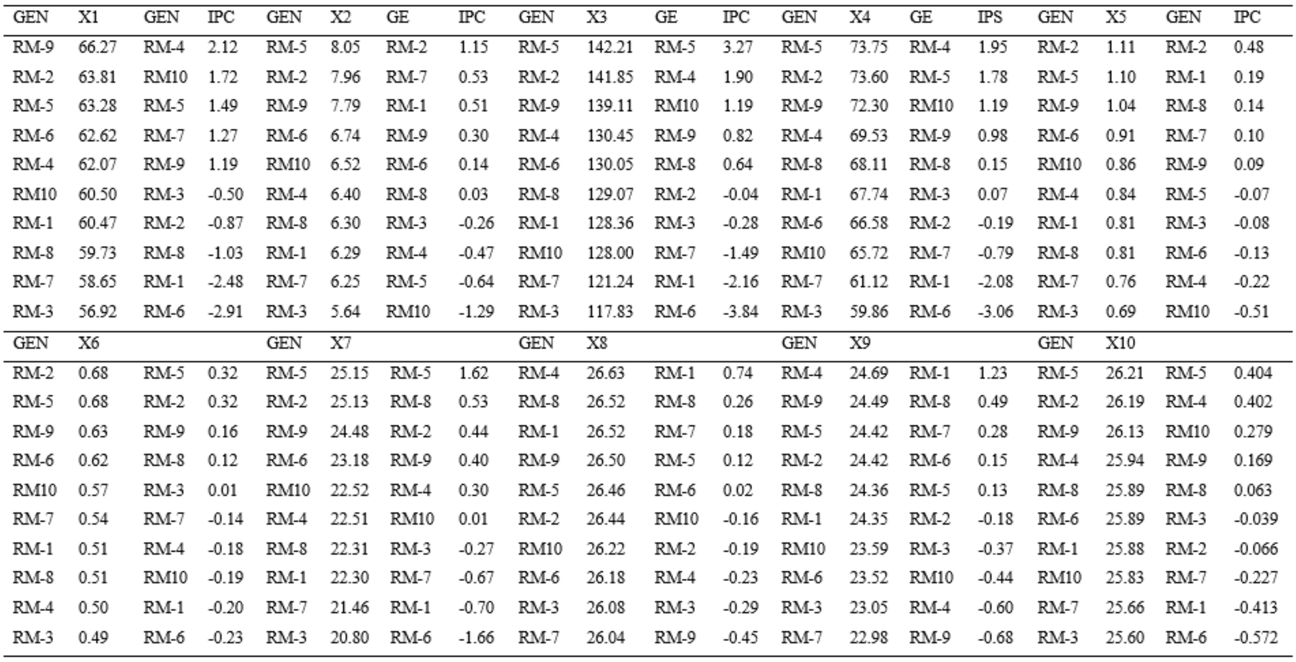
Table 5. Ranking for AMMI1 and AMMIF and winners for the AMMI model Family for the ten traits of rosemary

Plant height (cm)				Branches per plant				Fresh Plant weight (g)				Dry plant weight (g)				Oil content (fresh %)			
WG	A	M	F	WG	A	M	F	WG	A	M	F	WG	A	M	F	WG	A	M	F
4	0	1	F	2	0	1	F	3	0	1	F	3	0	1	F	3	0	1	F
RM-4	-	-	1	RM-2	-	2	2	RM-5	3	2	1	RM-4	-	-	1	RM-2	3	2	2
RM-9	3	1	-	RM-5	3	1	1	RM-2	-	-	1	RM-5	3	2	1	RM-5			1
RM-8	-	-	1	-	-	-	-	RM-6	-	1	1	RM-6	-	1	1	RM-10		1	
RM-6	-	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ME	1	2	3	ME	1	2	2	ME	1	2	3	ME	1	2	3	ME	1	2	2

Oil content (shade dried %)				1,8-cineole (in fresh aerial parts)				Camphor (in fresh aerial parts)				1,8-cineole (in dry aerial parts)				Camphor (in dry aerial parts)			
WG	A	M	F	WG	A	M	F	WG	A	M	F	WG	A	M	F	WG	A	M	F
3	0	1	F	3	0	1	F	3	0	1	F	2	0	1	F	3	0	1	F
RM-5	-	-	1	RM-5	3	2	1	RM-1	-	2	2	RM-1		2	2	RM-5	3	2	1
RM-2	3	1	2	RM-2	-	-	1	RM-4	3	-	1	RM-4	3	1	1	RM-2	-	-	1
RM-6	-	2	-	RM-6	-	1	1	RM-9	-	1	-	-	-	-	-	RM-6	-	1	1
ME	1	2	2	ME	1	2	3	ME	1	2	2	ME	1	2	2	ME	1	2	3

Notes. WG - Winner genotype = AM = (AMMI: Additive Main effects and Multiplicative Interaction); M = Model; FM = Family; IPC = Interaction principal component; G = Genotype; ENV: Environment; ME: Mega-environments.

Table 6. Genotypes ranked means (x̄) and IPC1 Scores over three environments for the ten traits of rosemary



GEN	X1	GEN	IPC	GEN	X2	GE	IPC	GEN	X3	GE	IPC	GEN	X4	GE	IPS	GEN	X5	GEN	IPC
RM-9	66.27	RM-4	2.12	RM-5	8.05	RM-2	1.15	RM-5	142.21	RM-5	3.27	RM-5	73.75	RM-4	1.95	RM-2	1.11	RM-2	0.48
RM-2	63.81	RM10	1.72	RM-2	7.96	RM-7	0.53	RM-2	141.85	RM-4	1.90	RM-2	73.60	RM-5	1.78	RM-5	1.10	RM-1	0.19
RM-5	63.28	RM-5	1.49	RM-9	7.79	RM-1	0.51	RM-9	139.11	RM10	1.19	RM-9	72.30	RM10	1.19	RM-9	1.04	RM-8	0.14
RM-6	62.62	RM-7	1.27	RM-6	6.74	RM-9	0.30	RM-4	130.45	RM-9	0.82	RM-4	69.53	RM-9	0.98	RM-6	0.91	RM-7	0.10
RM-4	62.07	RM-9	1.19	RM10	6.52	RM-6	0.14	RM-6	130.05	RM-8	0.64	RM-8	68.11	RM-8	0.15	RM10	0.86	RM-9	0.09
RM10	60.50	RM-3	-0.50	RM-4	6.40	RM-8	0.03	RM-8	129.07	RM-2	-0.04	RM-1	67.74	RM-3	0.07	RM-4	0.84	RM-5	-0.07
RM-1	60.47	RM-2	-0.87	RM-8	6.30	RM-3	-0.26	RM-1	128.36	RM-3	-0.28	RM-6	66.58	RM-2	-0.19	RM-1	0.81	RM-3	-0.08
RM-8	59.73	RM-8	-1.03	RM-1	6.29	RM-4	-0.47	RM10	128.00	RM-7	-1.49	RM10	65.72	RM-7	-0.79	RM-8	0.81	RM-6	-0.13
RM-7	58.65	RM-1	-2.48	RM-7	6.25	RM-5	-0.64	RM-7	121.24	RM-1	-2.16	RM-7	61.12	RM-1	-2.08	RM-7	0.76	RM-4	-0.22
RM-3	56.92	RM-6	-2.91	RM-3	5.64	RM10	-1.29	RM-3	117.83	RM-6	-3.84	RM-3	59.86	RM-6	-3.06	RM-3	0.69	RM10	-0.51
GEN	X6			GEN	X7			GEN	X8			GEN	X9			GEN	X10		
RM-2	0.68	RM-5	0.32	RM-5	25.15	RM-5	1.62	RM-4	26.63	RM-1	0.74	RM-4	24.69	RM-1	1.23	RM-5	26.21	RM-5	0.404
RM-5	0.68	RM-2	0.32	RM-2	25.13	RM-8	0.53	RM-8	26.52	RM-8	0.26	RM-9	24.49	RM-8	0.49	RM-2	26.19	RM-4	0.402
RM-9	0.63	RM-9	0.16	RM-9	24.48	RM-2	0.44	RM-1	26.52	RM-7	0.18	RM-5	24.42	RM-7	0.28	RM-9	26.13	RM10	0.279
RM-6	0.62	RM-8	0.12	RM-6	23.18	RM-9	0.40	RM-9	26.50	RM-5	0.12	RM-2	24.42	RM-6	0.15	RM-4	25.94	RM-9	0.169
RM10	0.57	RM-3	0.01	RM10	22.52	RM-4	0.30	RM-5	26.46	RM-6	0.02	RM-8	24.36	RM-5	0.13	RM-8	25.89	RM-8	0.063
RM-7	0.54	RM-7	-0.14	RM-4	22.51	RM10	0.01	RM-2	26.44	RM10	-0.16	RM-1	24.35	RM-2	-0.18	RM-6	25.89	RM-3	-0.039
RM-1	0.51	RM-4	-0.18	RM-8	22.31	RM-3	-0.27	RM10	26.22	RM-2	-0.19	RM10	23.59	RM-3	-0.37	RM-1	25.88	RM-2	-0.066
RM-8	0.51	RM10	-0.19	RM-1	22.30	RM-7	-0.67	RM-6	26.18	RM-4	-0.23	RM-6	23.52	RM10	-0.44	RM10	25.83	RM-7	-0.227
RM-4	0.50	RM-1	-0.20	RM-7	21.46	RM-1	-0.70	RM-3	26.08	RM-3	-0.29	RM-3	23.05	RM-4	-0.60	RM-7	25.66	RM-1	-0.413
RM-3	0.49	RM-6	-0.23	RM-3	20.80	RM-6	-1.66	RM-7	26.04	RM-9	-0.45	RM-7	22.98	RM-9	-0.68	RM-3	25.60	RM-6	-0.572

Notes. x̄ = Mean; IPS= IPC1 Score; GE= genotype; ENV=environment.

Table 7. Traits and environment ranked means and IPC1 Scores over three environments for the ten traits in rosemary

Traits	ENV	x̄	ENV	IPS	Traits	ENV	x̄	ENV	IPS
X1	ENV1	62.29	ENV3	4.35	X6	ENV1	0.59	ENV1	0.53
	ENV2	61.65	ENV1	-1.44		ENV3	0.57	ENV2	-0.26
	ENV3	60.36	ENV2	-2.91		ENV2	0.56	ENV3	-0.27
X2	ENV1	6.96	ENV2	1.14	X7	ENV1	23.35	ENV1	1.79
	ENV2	6.73	ENV1	0.52		ENV2	22.89	ENV3	0.18
	ENV3	6.69	ENV3	-1.66		ENV3	22.70	ENV2	-1.98
X3	ENV1	133.13	ENV1	2.86	X8	ENV1	26.40	ENV1	0.48
	ENV2	130.52	ENV3	2.19		ENV2	26.39	ENV2	0.36
	ENV3	128.80	ENV2	-5.05		ENV3	26.29	ENV3	-0.84
X4	ENV1	69.33	ENV3	2.45	X9	ENV1	24.13	ENV2	0.79
	ENV2	67.75	ENV1	1.49		ENV2	24.07	ENV1	0.63
	ENV3	66.42	ENV2	-3.94		ENV3	23.76	ENV3	-1.43
X5	ENV1	0.92	ENV1	0.41	X10	ENV1	25.98	ENV3	0.48
	ENV2	0.89	ENV2	0.24		ENV2	25.92	ENV1	0.32
	ENV3	0.87	ENV3	-0.65		ENV3	25.87	ENV2	-0.81

Notes. x̄ = mean**;** ENV = environment (ENV1=Lucknow, ENV2=Pantnagar, Env3= Hyderabad); IPS= IPC1 Score; GEN= genotype, ENV= environment, TRT=treatment, X1=Plant height (cm), X2=Branches per plant, X3= Fresh Plant weight (g), X4= Dry plant weight (g), X5=Oil content (fresh %), X6=Oil content (shade dried%), X7=1,8-cineole (in fresh aerial parts), X8= Camphor (in fresh aerial parts), X9= 1,8-cineole (in dry aerial parts), X10= Camphor (in dry aerial parts).

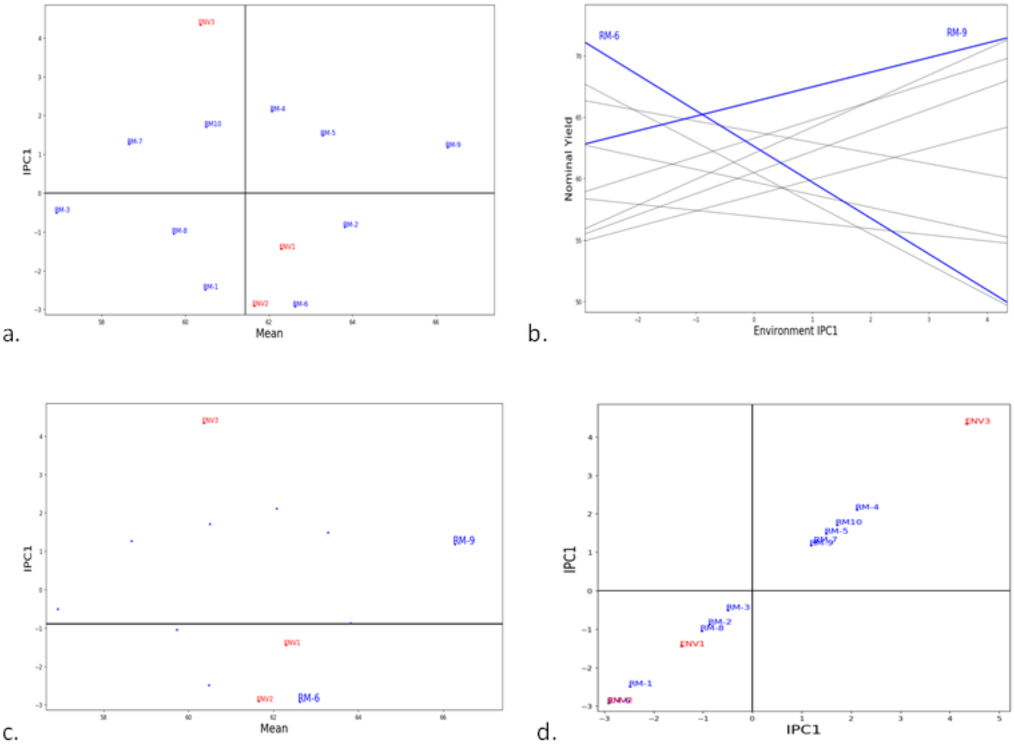


Figure 1(a-d). The scattered distribution patterns of genotypes, with mean, IPC and environment IPC adaptive responses by AMMI1 model in rosemary for Plant height (cm).

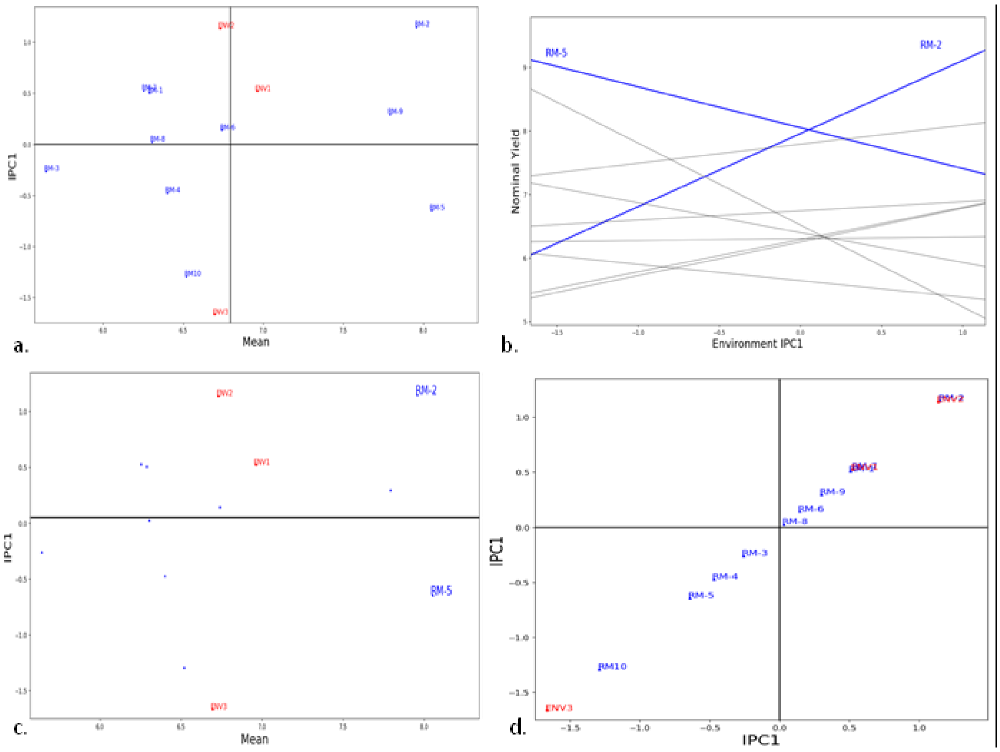


Figure 2(a-d). The scattered distribution patterns of genotypes, with mean, IPC and environment IPC adaptive responses by AMMI1 model in rosemary for branches per plant.

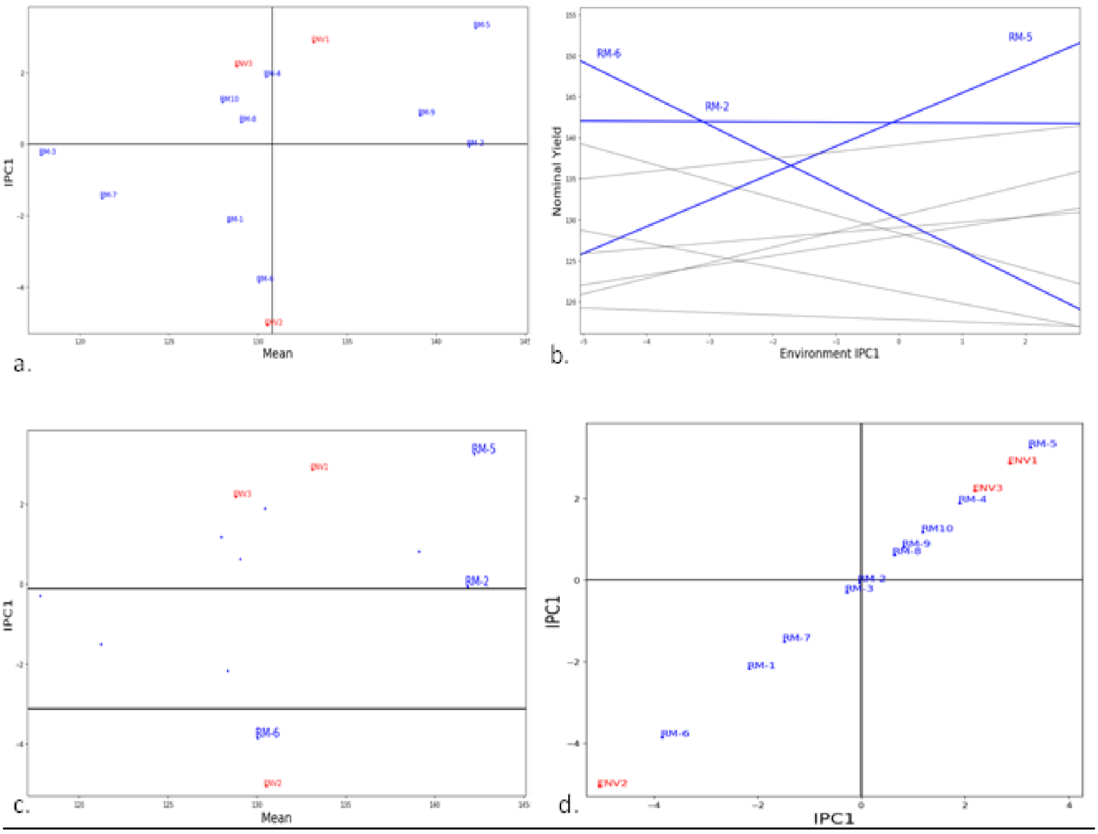


Figure 3(a-d). The scattered distribution patterns of genotypes, with mean, IPC and environment IPC adaptive responses by AMMI1 model in rosemary for fresh Plant weight (g).

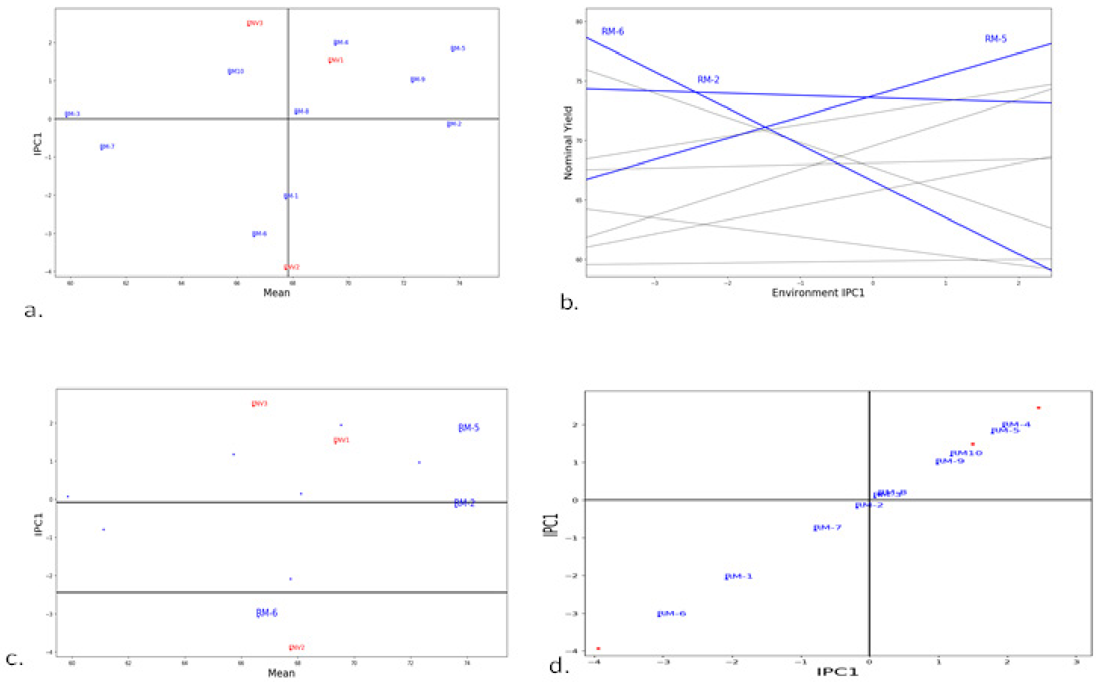


Figure 4 (a-d). The scattered distribution patterns of genotypes, with mean, IPC and environment IPC adaptive responses by AMMI1 model in rosemary for dry plant weight (g).

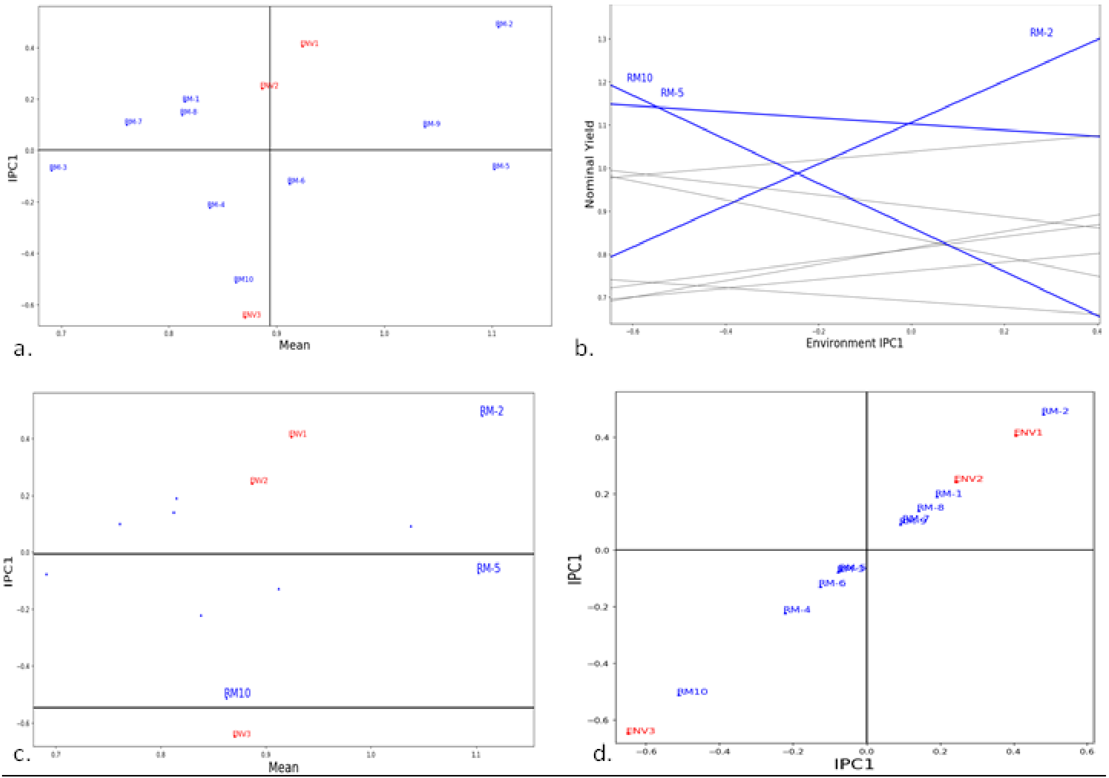


Figure 5 (a-d). The scattered distribution patterns of genotypes, with mean, IPC and environment IPC adaptive responses by AMMI1 model in rosemary for the essential oil content (fresh %).

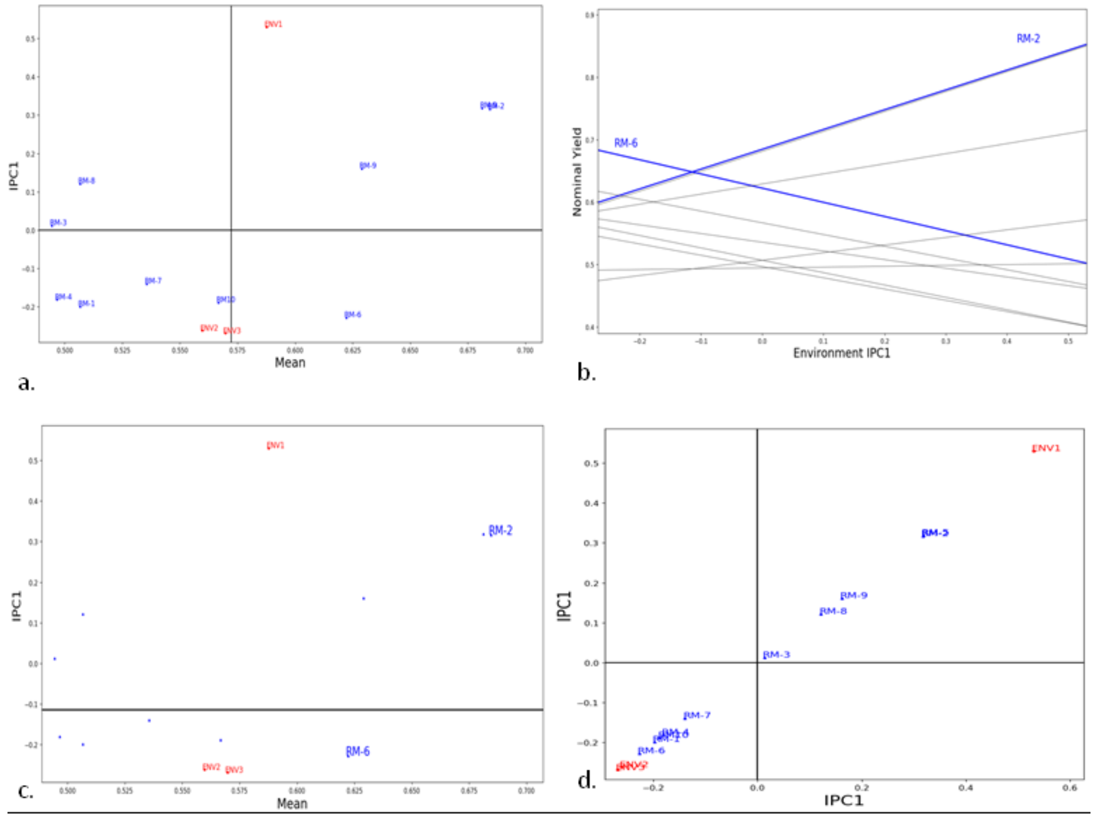


Figure 6 (a-d). The scattered distribution patterns of genotypes, with mean, IPC and environment IPC adaptive responses by AMMI1 model in rosemary for the Essential oil content (shade dried %).

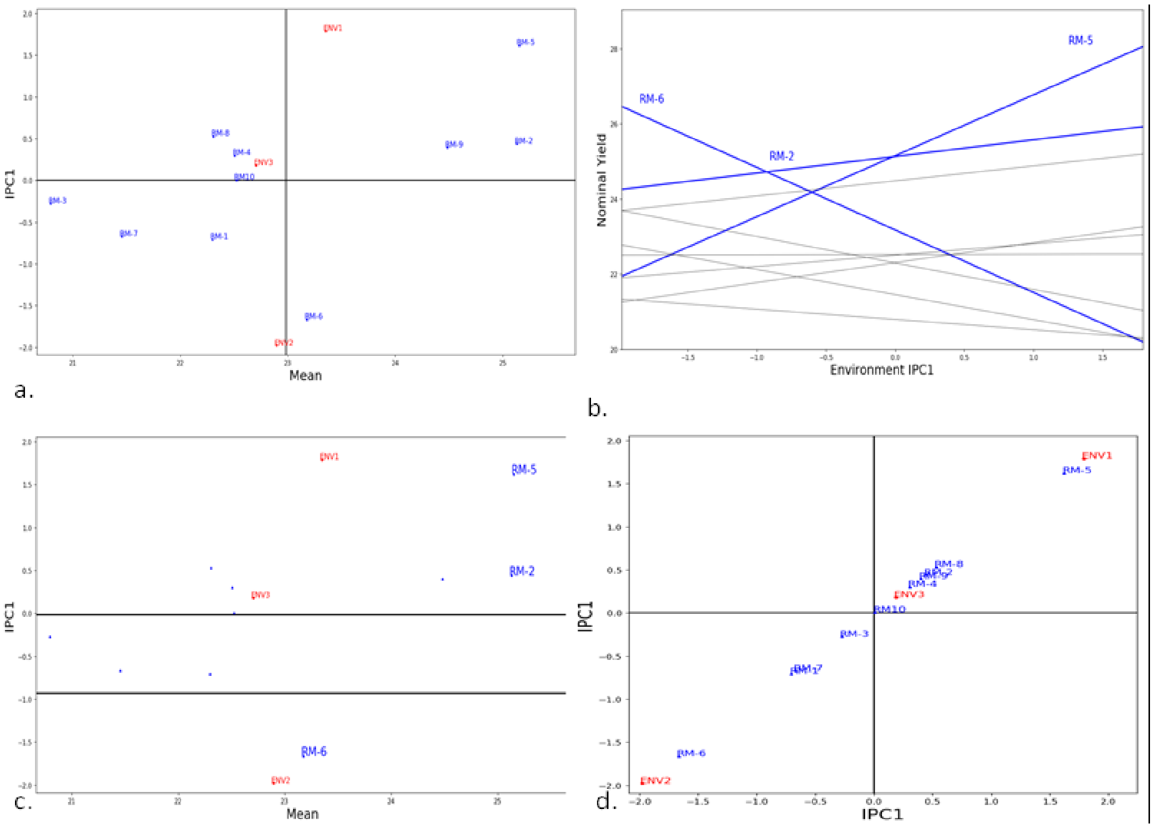


Figure 7 (a-d). The scattered distribution patterns of genotypes, with mean, IPC, and environment IPC adaptive responses by the AMMI1 model in rosemary for the 1,8-cineole (in fresh aerial parts).

Selected high-yielding lines were used in location trials to evaluate their stability across different environments.. To further assess the complex data generated by the interplay of location and genotype parameters, an appropriate statistical analytical method is required [23-25]. The merits and demerits of different stability models are the subject of intense debate in recent years [26-29]. In most studies, it is important to distinguish signal from noise and to use the AMMI model to evaluate genotypes, environments, and G×E interactions [30-33].

Mega-environments (M-e) analysis of the attributes from X1, 2, 3, followed by 4-10 in the experimental trial, yielded more useful findings. There is an obvious agricultural implication to the genotype difference that correlates with the location difference in their IPC1 rank. It reduces a large proportion of G×E noise but may overlook certain GES effects. The potential to increase anticipated accuracy serves as another argument for the significance of model diagnosis. M-e ranged from AMMI0 -AMMIF (Table 4).

The AMF, however, had the best anticipated accuracy over 3 locations in this study. GEIS and GEIN together comprise the whole var. of the GEI and GEIN [34-38]. However, whereas accession farthest is highly vulnerable to large interaction, genotypes closer to the ‘0’ were unaffected by interactions [39-41]. Similar patterns of interaction are seen in closely related lines or years as opposed to distant ecosystems [42-47]. The AMF identified 3 mega-environments and three stable lines, RM 5, RM 2, and RM 8, providing the most accurate approach for evaluating essential oil content (shade-dried %) in the current dataset. Furthermore, there are noteworthy correlations between the attributes that impact stability performance either directly or indirectly. The study’s findings were particularly intriguing because the majority of the features were highly significant and significantly correlated with both the fresh and shade-dried percentages of essential oil content. Weak positive or negative correlations were seen between the other qualities, specifically X6 × X8 and X6 × X9 (Figure 8).

Nevertheless, the genotypes for the fresh herb’s essential oil content (%) were RM 2, RM 1, and RM 8. The top-performing genotypes in rosemary were RM 4, RM 10, and RM 5 for plant height (cm); RM 2, RM 7, and RM 1 for branches per plant; RM 5, RM 4, and RM 10 for fresh plant weight (g); RM 4, RM 5, and RM 10 for dry plant weight (g); RM 5, RM 8, and RM 2 for 1,8-cineole (in fresh aerial parts); RM 1, RM 7, and RM 8 for camphor (in fresh aerial parts); and RM 1, RM 1, RM 8, and RM 7 for the traits 1,8-cineole (in dry aerial parts) (Table 7, Figure 9). Traditional breeding methods are also being combined with contemporary methods like correlations and stability in multi-location trials, to speed up the more promising trait of interest. Finally, the 3 lines—RM 5, RM 2, and RM 4—were chosen and suggested for additional production in India based on the IPC1 Scores and averages for the three locations.

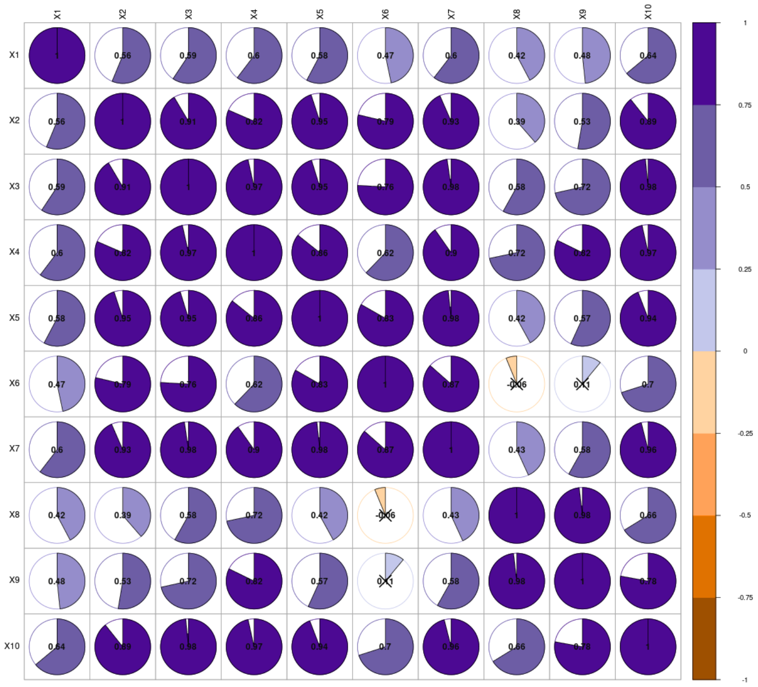


Figure 8. The correlogram between ten different traits in the rosemary

Table 8. The top three genotypes and environments rank based on the IPC1 Scores and means over the three environments for the ten traits of rosemary

Traits	Codes	Top three genotype ranks			Favorable environment ranks		
Ranks based on the IPC1 Scores		Rank1	Rank 2	Rank 3	Rank 1	Rank 2	Rank 3
Plant height (cm)	X1	RM-4	RM-10	RM-5	1	2	3
Branches per plant	X2	RM-2	RM-7	RM-1	1	2	3
Fresh plant weight (g)	X3	RM-5	RM-4	RM-10	1	2	3
Dry plant weight (g)	X4	RM-4	RM-5	RM-10	1	2	3
Oil content (fresh %)	X5	RM-2	RM-1	RM-8	1	2	3
Oil content (shade dried (%)	X6	RM-5	RM-2	RM-9	1	2	3
1,8-cineole (in fresh aerial parts)	X7	RM-5	RM-8	RM-2	1	2	3
Camphor (in fresh aerial parts)	X8	RM-1	RM-7	RM-8	1	2	3
1,8-cineole (in dry aerial parts)	X9	RM-1	RM-8	RM-7	2	1	3
Camphor (in dry aerial parts)	X10	RM-5	RM-4	RM-10	3	1	2
Ranks based on the basis of mean		Rank1	Rank 2	Rank 3	Rank 1	Rank 2	Rank 3
Plant height (cm)	X1	RM-9	RM-2	RM-5	1	2	3
Branches per plant	X2	RM-5	RM-2	RM-9	1	2	3
Fresh Plant weight (g)	X3	RM-5	RM-2	RM-9	1	2	3
Dry plant weight (g)	X4	RM-5	RM-2	RM-9	1	2	3
Oil content (fresh %)	X5	RM-2	RM-5	RM-9	1	2	3
Oil content (shade dried (%)	X6	RM-2	RM-5	RM-9	1	2	3
1,8-cineole (in fresh aerial parts)	X7	RM-5	RM-2	RM-9	1	2	3
Camphor (in fresh aerial parts)	X8	RM-4	RM-8	RM-1	1	2	3
1,8-cineole (in dry aerial parts)	X9	RM-4	RM-9	RM-5	1	2	3
Camphor (in dry aerial parts)	X10	RM-5	RM-2	RM-9	1	2	3

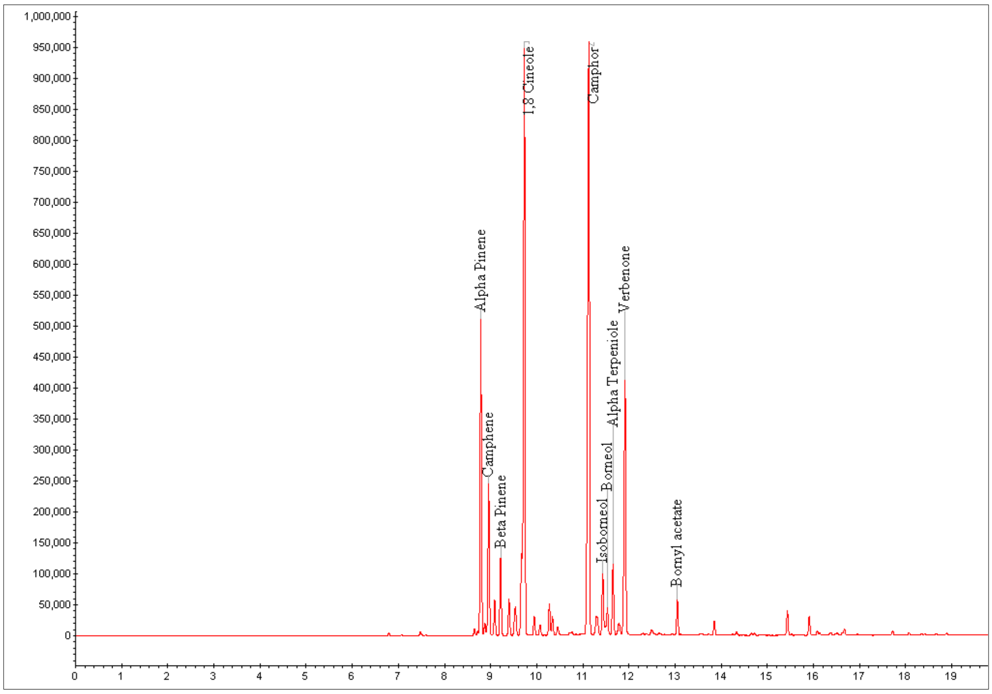


Figure 9. The chromatogram of the essential oil of the RM 5 of rosemary.

5. Conclusion

The rosemary cultivation area can be expanded to other locations by developing and releasing new varieties that thrive well in a range of agroclimatic conditions. The current investigation used the AMMI method on the ten lines of rosemary across three sites in Indian states. The year and location effects showed significant impacts on essential oil yield. These relationships also affect genotype stability. The finding complicates plant breeding operations due to the substantial impact of data integration. Based on the IPC1 Scores and averages for the three locations, three genotypes—RM 5, RM 2, and RM 4—were selected and recommended for further production in India.

Abbreviations

AMMI = Additive Main effects and Multiplicative Interaction, ANOVA = Analysis of variance, ENV = Environment, EO = Essential oil, EOY = Essential oil yield, G = Genotype, GEN = Genotype, G × E = Genotype × environment, GEI = G × E interactions, IPC = Interaction principal component. IPCA1 = first interaction principal component, M-e = Mega environments, r = correlation, RCBD = Randomized Complete Block Design, SS = Sum of squares, T = treatments.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Credit the author’s statement

AK and RKL were involved in planning, experimentation, manuscript preparation, and statistical analyses; AS and ACJ were involved in distillation and data collection, data curation; CS was involved in chemical fingerprinting/ chemical analysis of essential oil, and GSC was involved in writing.

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