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Genotype-environment interactions in basil lead to the development of stable genotypes through convergent selection

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ABSTRACT

Field investigations were performed at CSIR-CIMAP in Lucknow, India, in 2022, 2023, and 2024 to evaluate the stability of genotypes. The associations between attributes in different environments were examined using principal component analysis (PCA) and the RBD two-factor design. Tea prepared with basil leaves is said to help with loose motions, rheumatic discomfort, and vomiting. Tea made with black pepper and basil leaves can help reduce high fevers. Antioxidants found in abundance in basil may promote longevity and good health. Currently, there is inadequate research on how genotype and environmental interactions (GE) impact the stability and diversification of basil crops. However, a multi-environment essential oil yield trial for the basil cultivars has not been conducted with any stability, reliability, or contemporaneous evaluations. Therefore, the current study's objective was to evaluate the stability, reliability, and suggestions for making essential oils from commercial genotypes. The current study's objective was to evaluate the stability, reliability, and recommendations for producing essential oils from commercial genotypes of basil. Twelve different basil cultivars were investigated in this study to examine which cultivars consistently yielded high levels of linalool oil in a variety of environments and seasons. Both PCA and the RBD two-factor designs have been demonstrated to be compatible with the separation of genotype and environment into sources of variation. The basil genotypes O-2, O-6, and O-10 for essential oil yield and linalool content (%) were found to be the most stable and adaptable due to their ability to withstand a wide range of climatic conditions throughout time. In light of this, it can be concluded that the genotypes/varieties O-6, OC-8, and OC-10 were the most stable and performed well in terms of linalool content (%) and essential oil yield. Significant genetic variation was also found in this basil sample, according to PCA, with PC1 through PC12 showing high variable data values. The PCA also revealed the considerable genetic variety in this set of basil materials. For instance, PCs 1 through 11 displayed wildly disparate data values. The twelve basil traits had matched maximum eigenvalues of 5.121 and a percentage of variances of 42.671. Variability and genotypes O-6, OC-8, and OC-10 were found to be useful for additional genetic advancement via heterosis breeding.

Kew words: Aromatic compounds; basil; cosmetic; environmental interactions; methyl chavicol; Stabile genotype

DISCOVERY SCIENTIFIC SOCIETY

1. INTRODUCTION

The genus *Ocimum*, which is a member of the Lamiaceae family, consists of numerous species of herbs and shrubs known as basil. The genus is thought to contain between 50 and 60 species, and these plants are economically valuable due to their innate capacity to produce essential oils (Lal et al., 2020, Lal et al., 2022, Kumar and Jnanesha, 2019). Steam distilling the herb yields a bright yellow, aromatic essential oil (Lal et al., 2000, Sastry et al., 2015, Kumar et al., 2016). The food, cosmetics, and pharmaceutical industries use the aromatic compounds found in essential oils—such as eugenol, methyl eugenol, citral, methyl chavicol, linalool, geraniol, and camphor—as raw materials. The antibacterial and insecticidal qualities of basil essential oils are widely recognized (Lal et al., 2021a, Lal et al., 2021b, Singh and Lal, 2021, Lal et al., 2023a, Lal et al., 2023b, Lal et al., 2023c, Lal et al., 2023d). Because of its pleasant scent and antibacterial properties, basil essential oil is a significant aroma chemical with applications in many industries, including food, pharmaceutical, cosmetic, and aromatherapy (Akcura et al., 2005, Jnanesha et al., 2019, Srivastava et al., 2021, Srivastava et al., 2022).

A variety of antioxidants found in basil may promote longevity and good health (Kumar et al., 2024, Kumar et al., 2025a, Kumar et al., 2025b). The species that comprise basil differ greatly in terms of their physical characteristics and the chemical components of their essential oils. Israel alone exports 4 million US dollars worth of basil to the fresh herb market annually. Basil is commonly planted as a pot herb for use in cooking (Yalçın et al., 2023). Additionally, it has a major impact on India's continuously growing herbal industry. In India's hot, humid regions, commercial basil species are planted so that growers and farmers can produce leaves. Over an area of around 3000 hectares, *O. gratissimum* and *O. basilicum* are mostly grown in the Indian states of Assam, West Bengal, Bihar, U.P., Haryana, Maharashtra, Punjab, M.P., and Jammu (Lal et al., 2021b). These basil crops produce 250–300 t of essential oils annually (Lal et al., 2021b). Methyl chavicol and linalool are the primary components of the 250 tonnes of basil oil that are estimated to be produced in India each year. Khusumohak, Vikarsudha, CIM-Saumya, CIM-Sharada, CIM-Surabhi, CIM-Ayu, CIM-Angana, CIM-Kanchan, CIM-Jyoti, and a hybrid of *O. basilicum* × *O. kilimandscharicum*, CIM Suvaas, and CIM Shishir are just a few of the basil varieties that CSIR-CIMAP, Lucknow, has successfully developed through research and development (Kumar et al., 2021, Kumar and Lal, 2022, Kumar et al., 2022).

In order to determine the best cultivar for India's agroclimate, this study will evaluate the basil cultivars for consistency in crucial yield across time. Studies on the stability and variety of basil crops through environmental interactions (GE) are quite rare. However, no stability or reliability investigations have been carried out or evaluated concurrently in a multi-environment essential oil yield study for the genotypes of basil. The goal of the current study was to assess the stability, reliability, and recommendations for producing essential oils from commercial genotypes.

2. MATERIALS AND METHODS

2.1. Plants Materials

The plants and seeds for all varieties of basil were provided by the CSIR-CIMAP in Lucknow, India. Twelve different genotypes of basil (O1 to O12) were used in this study (Table 1). These basil cultivars were grown in the research farm CSIR-CIMAP, Lucknow (India), and using only standard agronomical methods.

2.2. Experimental site

Field experiments were carried out in the two-factor RBD in the three replications with plot size = 4.0 m^2 for three years from 2022, 2023, and 2024 at the CSIR-CIMAP, Lucknow (India), in order to assess the stability of genotypes.

2.3. Experiments

Over the course of three years (2022, 2023, and 2024), three replications of the experiments were carried out in the two-factor RBD. Every intercultural operation was carried out as needed. All genotypes/varieties of basil were transplanted with a 50 × 50 cm spacing in all experiments. Two split doses of 50 kg ha^{-1} nitrogen were delivered at 15-day intervals. Twenty-five and forty-five days after seedling transplanting, weeds were manually eradicated. Before planting, each plot got 1.5 t /ha of vermicompost, 40 kg/ ha of DAP, and 40 kg/ ha of K_2O.

Table 1. Basil genotype details with places of collections

S.No.	Genotypes	Origin/ places of collection
1.	O1	CIM Soumya (CSIR-CIMAP, Lucknow)
2.	O2	CIM Surabhi (CSIR-CIMAP, Lucknow)
3.	O3	Tamilnadu
4.	O4	Rameshwaram
5.	O5	Trissur
6.	O6	Tamilnadu
7.	O7	Trivandrum
8.	O8	Krishna Nagar, West Bengal
9.	O9	Madurai
10.	O10	Bareilly, Uttar Pradesh
11.	O11	Chennai, Tamil Nadu
12.	O12	Jodhpur, Rajasthan

2.4. Observations

The data were recorded on the 12 traits namely, X1 = plant height (cm); X2 = branches/plant; X3 = leaves/plant; X4 = leaf area (cm^2); X5 =herb yield (tonnes/ha); X6 = essential oil content (%); X7 = essential oil yield (kg/ha); X8 = methyl chavicol (%); X9 = linalool (%); X10 = eugenol (%); X11 = methyl content (%).; X12 = camphor content (%).

2.5. Distillation

Harvested crops were hydro-distilled for three hours using 500 g of each sample using Clevenger's apparatus (Clevenger, 1928). After being dried over anhydrous sodium sulfate, the oil was gathered and stored in sealed glass vials with a 5 ml capacity at 4ºC for testing and chemical analysis.

2.6. GC and GC-MS analysis

The standard approach was used to conduct the GC and GC-MS tests (Pragadheesh et al., 2013, Chanotiya et al., 2024). As the mobile phase (carrier), helium (He) was used at a steady gas flow rate of 1 mL/min. The mass scan period was 0.39 seconds with an inter-scan delay of 0.01 seconds, the interface (transfer line) temperatures were set at 290°C, and the gaseous ions were ionized using the electron impact ionization (EI) mode. Each component's mass spectra were recorded within the targeted mass range of 40 to 450 amu. A standardized series of saturated alkanes (C7-C30, CRM, 49451-U, Sigma-Aldrich) and the ninth edition of a mass spectral data reference book (Adams, 2007) were utilized to characterize the constituents using the relative retention index (RRI).

2.7. Statistical analysis

Each variety was observed for each of the 12 traits. The RBD two-factor design and Principal component analysis (PCA) were performed to explore the interrelationships among traits under different environments. PCA was carried out using PAST version 4.17. The resultant data from these programs includes the ANOVA, PCA analysis, genotype, and genotype × environment interactions. In this study, years are considered as environments.

3. RESULTS & DISCUSSION

In the combined ANOVA of the mean of the twelve basil traits, the genotypes and treatments were highly significant for each of the twelve traits. Except for the X2, X3, and X9 traits, which were only significant at $P<0.05\%$, the G × E is likewise highly significant for all traits. The environment (E) was also very significant for the majority of traits, with the exception of the X2 trait (Table 2). It demonstrated how the genotypes of basil differ greatly from one another. When selecting basil genotypes for the essential oil yield and stability, GEI remains a challenging issue for breeders who conduct field trials of genotype performance under different conditions or in different places. Using the AMMI model for GEI can improve the efficiency of basil breeders' efforts to choose stable and well-liked cultivars (Shukla, 1972, Kang and Pham, 1991, Gupta et al., 2021a, Gupta et al., 2021b, Jaiswal et al., 2021). The mean yields of the twelve varieties of basil varied from 112.91 to 148.38 kg/ha during three consecutive years (Tables 3-6).

Table 2. Combined analysis of variance (ANOVA) for the twelve traits in basil genotypes

Source of variation	d.f.	Mean Sum of Squares											
		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
Treatment	35	737.91**	15.15**	5313.82**	1.76**	105.24**	0.014**	788.56**	711.91**	2587.89**	216.26**	727.45**	827.681**
Genotype (G)	11	2327.76**	32.27**	16058.69**	2.53**	318.25**	0.042**	2104.41**	2253.00**	8176.44**	685.89**	2314.26**	2620.865**
Environment (E)	2	45.64**	10.14	829.92*	2.81**	37.53**	0.009**	588.56**	234.43*	123.76**	30.73**	30.53*	16.957**
G × E	22	15.92**	7.05*	349.01*	1.27**	24.90**	0.001**	148.82**	222.96**	127.63*	41.03**	40.13**	4.791**
IPC1	12	7.18	12.57**	566.71**	2.06**	8.23	0.001**	265.25**	4.47	32.16	1.53	0.19	8.781**
Residual	10	4.41	0.43	87.77	0.32	0.90	0.0002	9.12	1.15	0.19	0.42	0.06	0.003
Error	72	6.26	4.16	170.18	0.33	6.66	0.0003	28.55	70.04	74.84	4.72	8.10	0.013
Total	107												

X1 = Plant height (cm); X2 = Branches per plant; X3 = Leaves per plant; X4 = leaf area (cm2); X5 =herb yield (tonnes/ha); X6 = Essential oil content (%); X7 = Essential oil yield (kg/ha); X8 = Methyl chavicol content (%); X9 = Linalool content (%); X10 = Eugenol content (%); X11 = Methyl eugenol content (%).; X12= Camphor (%).

Table 3. Mean performance for the genotype (G) and environment (E) over the three years in basil

Genotype (G)	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
O1	57.54	20.04	183.23	8.84	18.89	0.58	112.92	22.66	7.80	0.31	0.068	12.5989
O2	78.96	18.98	114.91	7.91	33.09	0.46	148.34	29.91	25.45	2.04	0.003	0.0167
O3	97.44	21.16	225.13	9.10	32.31	0.40	128.09	28.66	0.58	21.88	25.581	0.0589
O4	92.35	16.61	152.65	8.04	26.67	0.53	147.13	0.39	22.75	10.68	23.120	0.0189
O5	57.69	20.10	183.26	8.87	18.90	0.58	112.92	22.69	7.82	0.33	0.068	12.5989
O6	78.99	16.82	114.99	7.95	33.10	0.48	148.38	29.93	25.45	2.05	0.003	0.0167
O7	97.50	21.19	225.19	9.14	32.43	0.44	128.12	28.67	0.60	21.89	25.581	0.0589
O8	92.41	16.67	152.75	8.07	26.66	0.57	147.15	0.40	22.77	10.69	23.120	0.0189
O9	57.71	20.11	183.24	8.88	18.89	0.60	112.91	22.69	7.81	0.32	0.068	12.5989
O10	79.02	19.04	114.98	7.96	33.10	0.48	148.36	29.93	25.45	2.05	0.003	0.0167
O11	97.48	21.24	225.17	9.12	32.39	0.43	128.14	28.67	0.59	21.89	25.581	0.0589
O12	92.35	16.64	152.75	8.02	26.66	0.56	147.07	0.40	22.77	10.69	23.120	0.0189
Environment (E)												
1	81.35	19.04	165.61	8.82	28.83	0.50	134.24	20.93	14.09	8.86	12.09	3.3758
2	82.86	19.58	174.51	8.33	27.64	0.53	138.11	19.36	14.41	8.71	12.25	3.2192
3	80.65	18.52	166.95	8.34	26.80	0.51	130.03	20.96	13.97	8.63	12.24	2.9250

X1 = Plant height (cm); X2 = Branches per plant; X3 = Leaves per plant; X4 = leaf area (cm2); X5 =herb yield (tonnes/ha); X6 = Essential oil content (%); X7 = Essential oil yield (kg/ha); X8 = Methyl chavicol content (%); X9 = Linalool content (%); X10 = Eugenol content (%); X11 = Methyl eugenol content (%).; X12= Camphor (%).

Table 4. Mean performance for the genotype × environment (G ×E) over the three years in basil.

Treatments	G×E	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
1	1×1	59.03	19.82	162.83	9.70	19.08	0.57	113.59	22.66	6.85	0.23	0.073	13.4200
2	2×1	79.16	19.87	111.38	7.38	34.38	0.43	146.42	32.01	25.38	1.85	0.003	0.0067
3	3×1	95.78	20.31	233.52	9.83	34.53	0.38	130.20	28.62	0.51	22.07	25.403	0.0700
4	4×1	91.12	16.00	154.35	8.25	27.32	0.52	146.73	0.38	23.58	11.27	22.863	0.0067
5	5×1	59.27	19.90	162.96	9.73	19.06	0.58	113.55	22.68	6.87	0.24	0.073	13.4200
6	6×1	79.20	19.90	111.49	7.40	34.40	0.46	146.47	32.03	25.38	1.87	0.003	0.0067
7	7×1	95.90	20.34	233.60	9.88	34.55	0.43	130.23	28.64	0.51	22.07	25.403	0.0700
8	8×1	91.15	16.07	154.53	8.29	27.32	0.56	146.75	0.39	23.59	11.29	22.863	0.0067
9	9×1	59.25	19.85	162.96	9.75	19.03	0.60	113.54	22.70	6.87	0.25	0.073	13.4200
10	10×1	79.30	19.90	111.57	7.45	34.42	0.45	146.44	32.05	25.39	1.87	0.003	0.0067
11	11×1	95.90	20.45	233.62	9.85	34.51	0.42	130.22	28.64	0.51	22.06	25.403	0.0700

12	12×1	91.17	16.07	154.45	8.28	27.34	0.55	146.72	0.39	23.60	11.29	22.863	0.0067
13	1×2	57.45	20.22	193.99	8.36	18.90	0.60	114.56	21.28	8.71	0.34	0.070	12.7833
14	2×2	81.18	19.34	120.65	7.54	33.33	0.47	155.31	27.51	25.67	2.69	0.003	0.0167
15	3×2	99.49	21.63	232.19	9.13	32.87	0.43	140.23	28.28	0.81	21.26	25.520	0.0433
16	4×2	93.15	16.99	151.15	8.18	25.29	0.55	142.31	0.34	22.39	10.53	23.413	0.0333
17	5×2	57.62	20.29	193.89	8.41	18.92	0.59	114.58	21.32	8.73	0.36	0.070	12.7833
18	6×2	81.22	19.43	120.72	7.57	33.35	0.49	155.34	27.53	25.68	2.69	0.003	0.0167
19	7×2	99.52	21.68	232.25	9.18	33.18	0.47	140.31	28.29	0.83	21.28	25.520	0.0433
20	8×2	93.25	17.05	151.20	8.21	25.25	0.59	142.32	0.35	22.41	10.52	23.413	0.0333
21	9×2	57.69	20.35	193.82	8.41	18.93	0.61	114.57	21.31	8.72	0.35	0.070	12.7833
22	10×2	81.20	19.33	120.70	7.58	33.33	0.49	155.32	27.52	25.68	2.68	0.003	0.0167
23	11×2	99.53	21.66	232.32	9.16	33.11	0.46	140.37	28.29	0.83	21.28	25.520	0.0433
24	12×2	92.99	17.00	151.26	8.20	25.23	0.59	142.14	0.36	22.41	10.53	23.413	0.0333
25	1×3	56.15	20.07	192.88	8.45	18.68	0.58	110.61	24.05	7.83	0.37	0.060	11.5933
26	2×3	76.53	17.75	112.70	8.82	31.55	0.47	143.29	30.22	25.29	1.57	0.003	0.0267
27	3×3	97.04	21.52	209.68	8.34	29.53	0.39	113.82	29.09	0.43	22.32	25.820	0.0633
28	4×3	92.79	16.82	152.45	7.70	27.40	0.52	152.36	0.45	22.27	10.23	23.083	0.0167
29	5×3	56.20	20.10	192.93	8.47	18.71	0.57	110.62	24.07	7.85	0.38	0.060	11.5933
30	6×3	76.57	11.12	112.75	8.89	31.54	0.51	143.33	30.24	25.30	1.58	0.003	0.0267
31	7×3	97.08	21.55	209.70	8.36	29.56	0.42	113.83	29.09	0.44	22.32	25.820	0.0633
32	8×3	92.83	16.88	152.52	7.72	27.40	0.56	152.38	0.46	22.30	10.25	23.083	0.0167
33	9×3	56.20	20.11	192.95	8.48	18.70	0.58	110.61	24.07	7.83	0.38	0.060	11.5933
34	10×3	76.56	17.88	112.68	8.86	31.56	0.50	143.32	30.22	25.29	1.59	0.003	0.0267
35	11×3	97.02	21.59	209.56	8.35	29.54	0.42	113.82	29.08	0.44	22.32	25.820	0.0633
36	12×3	92.87	16.85	152.55	7.59	27.40	0.54	152.35	0.46	22.31	10.25	23.083	0.0167

Table 5. Genotype (G), environment (E), and G × E related SE, SED, CD and GM over the three years in basil.

Genotype (G)	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
SE	8.29	3.19	43.38	0.23	3.11	0.03	16.68	9.72	9.26	5.30	9.41	3.21
SED	11.73	4.51	61.35	0.33	4.40	0.04	23.59	13.74	13.10	7.49	13.31	4.53
CD 5%	23.23	8.93	121.46	0.65	8.71	0.08	46.70	27.21	25.94	14.84	26.35	8.98
CD 1%	30.85	11.86	161.34	0.87	11.57	0.10	62.03	36.14	34.46	19.71	35.00	11.92
Environment (E)												
SE	4.15	1.60	21.69	0.47	1.56	0.01	8.34	4.86	4.63	2.65	4.71	1.60
SED	5.87	2.26	30.67	0.66	2.20	0.02	11.79	6.87	6.55	3.75	6.65	2.27
CD 5%	11.61	4.47	60.73	1.30	4.36	0.04	23.35	13.60	12.97	7.42	13.18	4.49
CD 1%	15.43	5.93	80.67	1.73	5.78	0.05	31.02	18.07	17.23	9.85	17.50	5.96
G × E												
SE	14.37	5.53	75.13	0.81	5.39	0.05	28.89	16.83	16.05	9.18	16.30	5.55
SED	20.32	7.81	106.25	1.14	7.62	0.07	40.85	23.80	22.69	12.98	23.05	7.85
CD 5%	40.23	15.47	210.38	2.26	15.09	0.13	80.89	47.12	44.93	25.70	45.64	15.55
CD 1%	53.43	20.55	279.45	3.00	20.04	0.17	107.45	62.59	59.69	34.14	60.63	20.65
GM	81.62	19.05	169.02	8.49	27.76	0.51	134.13	20.42	14.15	8.73	12.19	3.17

X1 = Plant height (cm); X2 = Branches per plant; X3 = Leaves per plant; X4 = leaf area (cm2); X5 =herb yield (tonnes/ha); X6 = Essential oil content (%); X7 = Essential oil yield (kg/ha); X8 = Methyl chavicol content (%); X9 = Linalool content (%); X10 = Eugenol content (%); X11 = Methyl eugenol content (%).; X12= Camphor (%); GM = grand mean, SE = Slandered error; SED = Slandered error difference; CD = Critical difference.

Descriptive statistics revealed a wide range of variation among the studied basil genotypes for all measured traits. The essential oil yield, quantity, and chemical composition of the genotypes varied significantly. The essential oil content of the genotypes ranged from

0.40 to 0.60%, essential oil yield: 112.91 to 148.38 kg/ha, methyl chavicol content (%): 0.39 to 29.93, linalool content (%): 0.58 to 25.45, eugenol content (%): 0.39 to 21.89, methyl eugenol content (%): 0.00 to 25.58, and camphor content (%): 0.02 to 12.60 %. The studied genotypes also showed range of variability for the plant height (57.54-97.50cm), branches per plant (16.61 – 21.24), leaves per plant (114.91 - 225.19), leaf area (cm^2) (7.91 -9.14), herb yield (tonnes/ha) (18.89 - 33.10), essential oil content (%) (0.40- 0.60) (Table 6). The average means of these traits were for the essential oil content (0.51), essential oil yield: 134.13, methyl chavicol content (%):20.42, linalool content (%): 14.15, eugenol content (%): 14.15, methyl eugenol content (%): 8.74, and camphor content (%): 12.19, respectively.

Table 6. Summary statistics Univariate for the twelve traits of basil

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
Min	57.54	16.61	114.91	7.91	18.89	0.40	112.91	0.39	0.58	0.31	0.00	0.02
Max	97.50	21.24	225.19	9.14	33.10	0.60	148.38	29.93	25.45	21.89	25.58	12.60
Sum	979.44	228.60	2028.25	101.90	333.09	6.11	1609.53	245.00	169.84	104.82	146.31	38.10
Mean	81.62	19.05	169.02	8.49	27.76	0.51	134.13	20.42	14.15	8.74	12.19	3.18
Std. error	4.64	0.55	12.19	0.15	1.72	0.02	4.41	3.58	3.11	2.58	3.68	1.64
Variance	258.69	3.59	1784.36	0.28	35.35	0.00	233.81	153.92	116.17	79.72	162.07	32.30
Stand. dev	16.08	1.89	42.24	0.53	5.95	0.07	15.29	12.41	10.78	8.93	12.73	5.68
Median	85.69	19.54	167.99	8.46	29.49	0.51	137.61	25.68	15.29	6.37	11.60	0.04
25 prcntil	63.02	16.71	124.41	7.98	20.84	0.45	116.71	5.97	2.40	0.76	0.02	0.02
75 prcntil	96.18	20.90	214.66	9.05	32.93	0.58	148.04	29.60	24.78	19.08	24.97	9.47
Skewness	-0.67	-0.32	0.08	0.09	-0.70	-0.16	-0.43	-1.13	-0.18	0.64	0.02	1.33
Kurtosis	-1.16	-1.66	-1.27	-2.21	-1.22	-1.57	-1.67	-0.57	-2.03	-1.29	-2.41	-0.33
Geom. mean	80.02	18.96	164.06	8.48	27.11	0.50	133.30	9.37	7.19	3.52	0.00	0.13
Coeff. var	19.71	9.94	24.99	6.27	21.42	13.52	11.40	60.77	76.15	102.22	104.41	179.01
N	12	12	12	12	12	12	12	12	12	12	12	12

X1 = Plant height (cm); X2 = Branches per plant; X3 = Leaves per plant; X4 = leaf area (cm^2); X5 =herb yield (tonnes/ha); X6 = Essential oil content (%); X7 = Essential oil yield (kg/ha); X8 = Methyl chavicol content (%); X9 = Linalool content (%); X10 = Eugenol content (%); X11 = Methyl eugenol content (%).; X12= Camphor (%).

Similarly, other traits also demonstrated the same patterns (Table 6; figures 1a-d to 6a-d). O7 (97.50) cm was the tallest plant among the tested genotypes, followed by O11 (97.48) and O3 (97.44) cm; genotype O1 was the shortest (57.54) cm. Similarly, the genotype O11 (21.24) had the most branches per plant, followed by O7 (21.19) and O3 (21.16), while the genotype O4 had the fewest branches per plant. Genotype O7 (225.19) had the most leaves per plant, followed by genotypes O11 (225.17) and O3 (225.13), while genotype O2 had 114.91 leaves. For example, the genotypes O6 and O10 had the highest percentage of methyl chavicol (29.93%), followed by O2 (29.91%), O7, and O11 (28.67%), while the genotype O4 had the lowest percentage (0.39%). O6 (148.38) kg/ha was the highest essential oil yield among the studied genotypes of basil, followed by O10 (138.36) and O2 (138.34). The genotype O9 had the lowest yield (112.91 kg/ha). Comparably, the genotypes O6 and O10 had the highest methyl chavicol content (%) (29.93%), followed by O2 (29.91%), O7, and O11 (28.67%), while the genotype O4 had the lowest (0.39%). The similar trends were also seen in other attributes (Table 6-7). When choosing genotypes for the variety recommendation, one of the most crucial factors to take into account is the yield of essential oils and their chemical components. The potential for selection and genetic enhancement of stable basil genotypes was highlighted by the overall results, which showed significant genetic variability among the investigated genotypes for all variables, including the essential oil production and quality yield-related traits. The existence of GEI was indicated by the varying rankings of the kinds in the different environments and locations (Table 8).

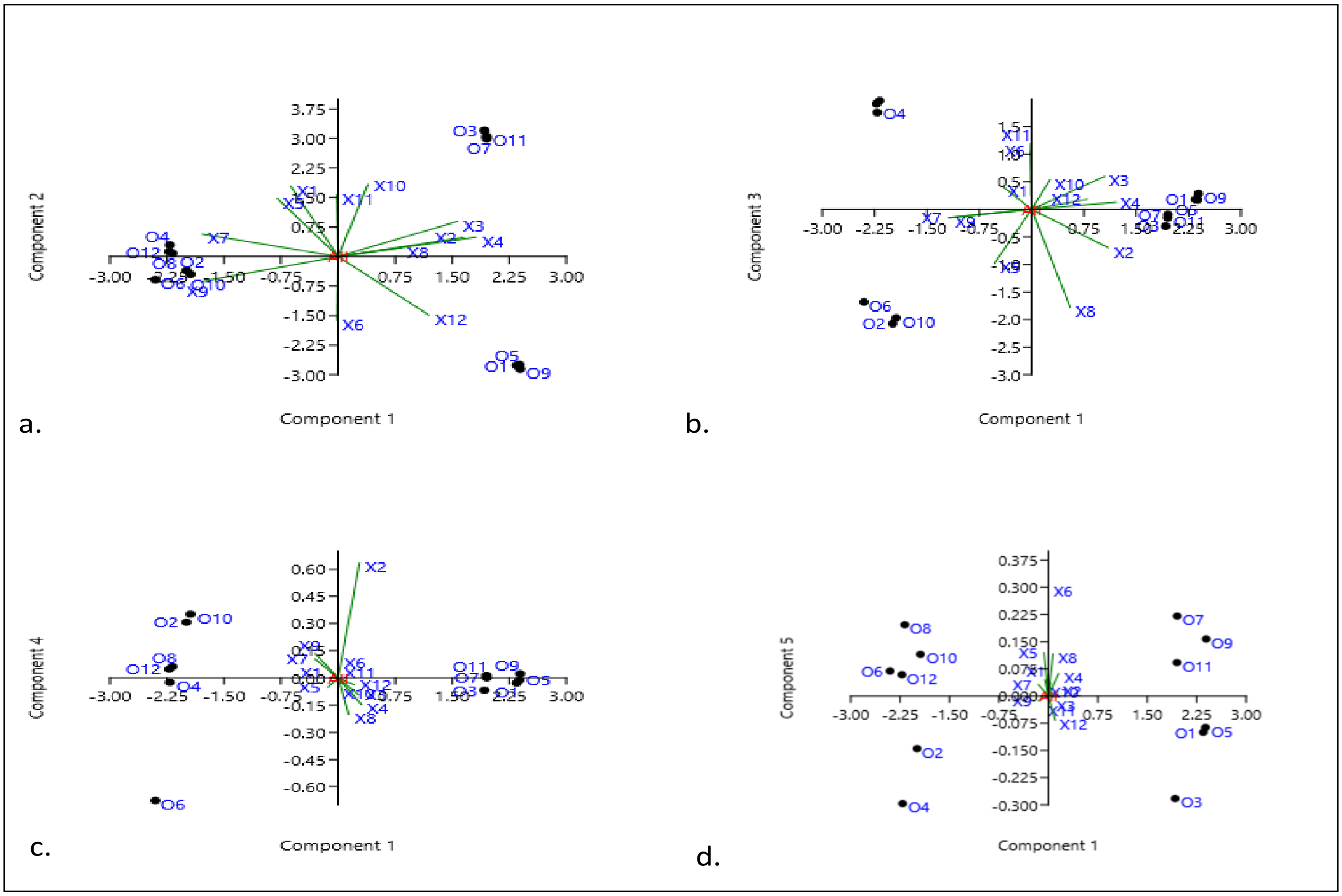

Figure 1a-d. Components (1 and 2 to 5) analysis in the twelve genotypes of basil

Table 7. The top three rankings and their averages from the 12 genotypes for the 12 traits in basil

Treats	Genotype (G) ranks			Genotype	Environment (E) ranks		
Mean	I	II	III	Lowest rank	I	II	III
X1	O7	O11	O3	O1	2	1	3
Mean	97.50	97.48	97.44	57.54	82.86	81.35	80.65
X2	O11	O7	O3	O4	2	1	3
Mean	21.24	21.19	21.16	16.61	19.58	19.04	18.52
X3	O7	O11	O3	O2	2	3	1
Mean	225.19	225.17	225.13	114.91	174.51	166.95	165.61
X4	O7	O11	O3	O2	1	3	2
Mean	9.14	9.12	9.10	7.91	8.82	8.34	8.33
X5	O6, O10	O2	O7	O1, O9	1	2	3
Mean	33.10	33.09	32.43	18.89	28.83	27.64	26.80
X6	O9	O1, O5	O8	O4	2	3	1
Mean	0.60	0.58	0.57	0.40	0.53	0.51	0.50
X7	O6	O10	O2	O9	2	1	3
Mean	148.38	148.36	148.34	112.91	138.11	134.24	130.03
X8	O6, O10	O2	O7, O11	O4	3	1	2
Mean	29.93	29.91	28.67	0.39	20.96	20.93	19.36
X9	O2, O6, O10	O8, O12	O4	O3	2	1	3
Mean	25.45	22.77	22.75	0.58	14.41	14.09	13.97
X10	O7, O11	O3	O8, O12	X10	1	2	3

Mean	21.89	21.88	10.69	0.31	8.86	8.71	8.63
X11	O3, O7, O11	O4, O8, O12	O1, O5, O9	O2, O6, O10	2	3	1
Mean	25.581	23.120	0.068	0.003	12.25	12.24	12.09
X12	O1, O5, O9	O3, O7, O11	O4, O8, O12	O2, O6, O10	1	2	3
Mean	12.5989	0.0589	0.0189	0.0167	3.3758	3.2192	2.9250

X1 = Plant height (cm); X2 = Branches per plant; X3 = Leaves per plant; X4 = leaf area (cm^2); X5 =herb yield (tonnes/ha); X6 = Essential oil content (%); X7 = Essential oil yield (kg/ha); X8 = Methyl chavicol content (%); X9 = Linalool content (%); X10 = Eugenol content (%); X11 = Methyl eugenol content (%).; X12= Camphor (%).

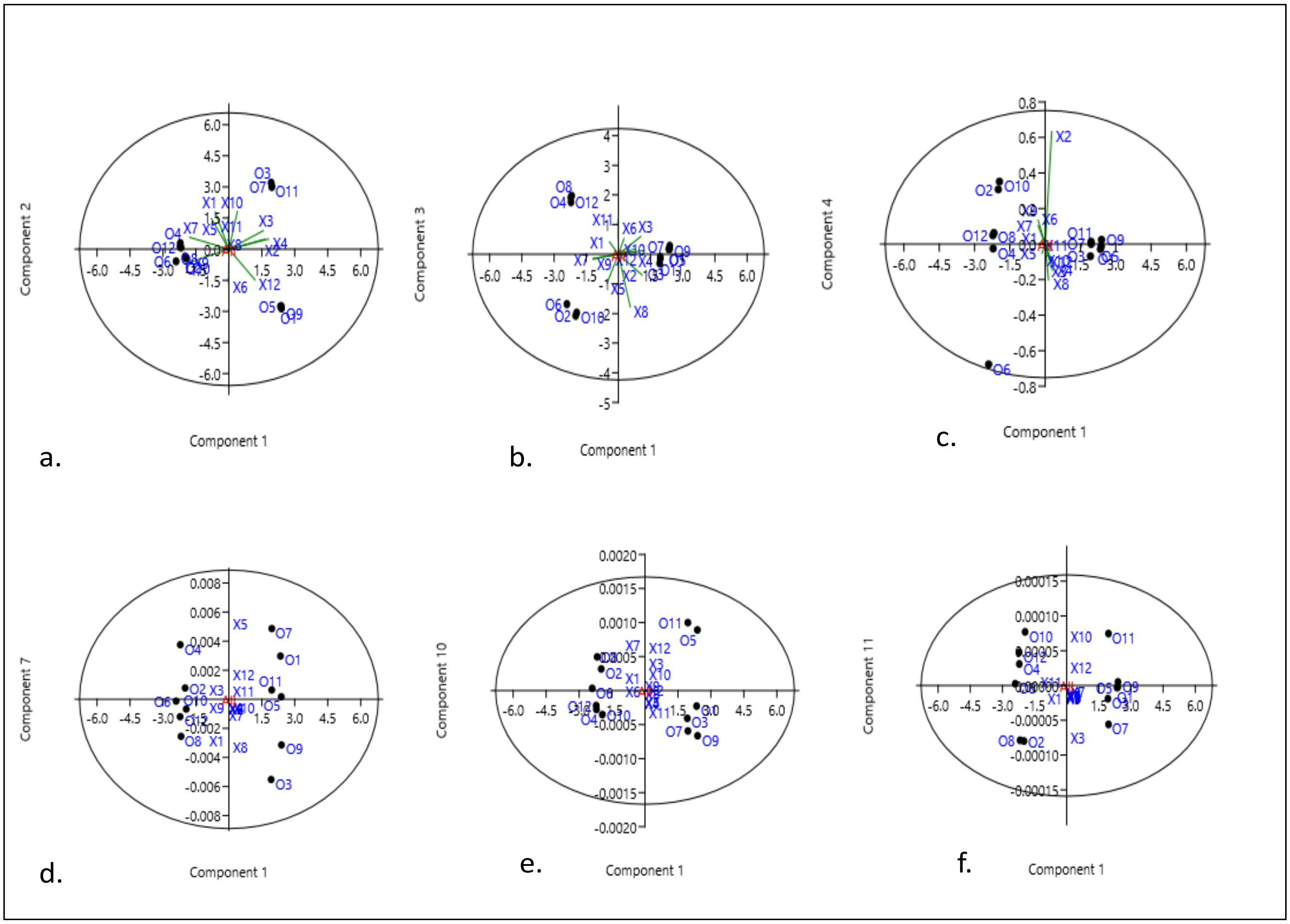

Figure 2a-f. Components (1 and 2-4 , and 7,10,11) analysis in the twelve genotypes of basil

Table 8. Principal component analysis data, eigenvalue and % variance for the 12 genotypes related to 12 traits of basil

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10	PC 11
O1	2.35	-2.76	0.18	-0.03	-0.10	-0.03	0.003	-0.00309	0.00026	-0.00023	0.00000
O2	-1.99	-0.36	-2.07	0.31	-0.15	-0.02	0.001	0.00089	-0.00054	0.00032	-0.00008
O3	1.92	3.20	-0.31	-0.07	-0.28	0.003	-0.006	-0.00041	0.00035	-0.00041	-0.00002
O4	-2.21	0.29	1.76	-0.02	-0.30	0.030	0.004	0.00027	-0.00056	-0.00028	0.00003
O5	2.38	-2.75	0.17	-0.01	-0.09	0.021	0.0002	0.00205	0.00081	0.00089	0.00000
O6	-2.40	-0.59	-1.68	-0.68	0.07	-0.0004	-0.0001	0.00002	-0.00001	0.00003	0.00000
O7	1.95	3.00	-0.09	0.00	0.22	0.007	0.005	0.00105	0.00036	-0.00059	-0.00006
O8	-2.18	0.08	1.97	0.06	0.20	0.018	-0.003	-0.00185	0.00006	0.00050	-0.00008
O9	2.39	-2.86	0.28	0.02	0.16	0.007	-0.003	0.00104	-0.00107	-0.00066	0.00001

O10	-1.94	-0.45	-1.97	0.35	0.12	0.025	-0.001	-0.00091	0.00055	-0.00035	0.00008
O11	1.95	3.05	-0.16	0.01	0.09	-0.010	0.001	-0.00065	-0.00071	0.00100	0.00007
O12	-2.22	0.12	1.92	0.05	0.06	-0.048	-0.001	0.00158	0.00050	-0.00022	0.00005
X1	-0.147	0.420	0.147	0.047	0.123	0.040	-0.394	0.635	-0.380	0.161	-0.161
X2	0.388	0.114	-0.246	0.880	0.036	0.008	0.000	-0.002	0.000	0.001	0.000
X3	0.369	0.210	0.211	-0.129	-0.006	-0.251	0.092	-0.072	0.362	0.391	-0.625
X4	0.426	0.115	0.045	-0.205	0.172	0.854	0.015	-0.024	0.029	-0.030	0.007
X5	-0.188	0.348	-0.345	-0.071	0.329	-0.026	0.755	0.197	-0.029	-0.018	-0.027
X6	-0.004	-0.381	0.375	0.122	0.830	-0.104	-0.007	-0.004	-0.003	-0.001	0.002
X7	-0.421	0.135	-0.055	0.145	0.088	0.226	-0.060	-0.562	-0.249	0.578	-0.076
X8	0.195	0.052	-0.627	-0.280	0.322	-0.197	-0.414	-0.047	0.073	0.088	0.041
X9	-0.416	-0.148	-0.053	0.187	-0.035	0.275	-0.074	0.338	0.696	0.176	-0.032
X10	0.092	0.430	0.187	-0.047	0.100	-0.155	-0.082	-0.075	0.337	0.216	0.698
X11	-0.005	0.369	0.417	0.073	-0.037	-0.058	0.076	-0.134	-0.021	-0.223	0.037
X12	0.281	-0.350	0.064	-0.052	-0.183	-0.042	0.271	0.311	-0.241	0.593	0.292
Eigenvalue	5.121	4.792	1.993	0.063	0.032	0.001	0.00001	0.000002	0.0000003	0.0000003	0.000000001
% variance	42.671	39.932	16.606	0.522	0.264	0.005	0.00007	0.00002	0.000003	0.000003	0.00000002

X1 = Plant height (cm); X2 = Branches per plant; X3 = Leaves per plant; X4 = leaf area (cm^2); X5 =herb yield (tonnes/ha); X6 = Essential oil content (%); X7 = Essential oil yield (kg/ha); X8 = Methyl chavicol content (%); X9 = Linalool content (%); X10 = Eugenol content (%); X11 = Methyl eugenol content (%).; X12= Camphor (%).

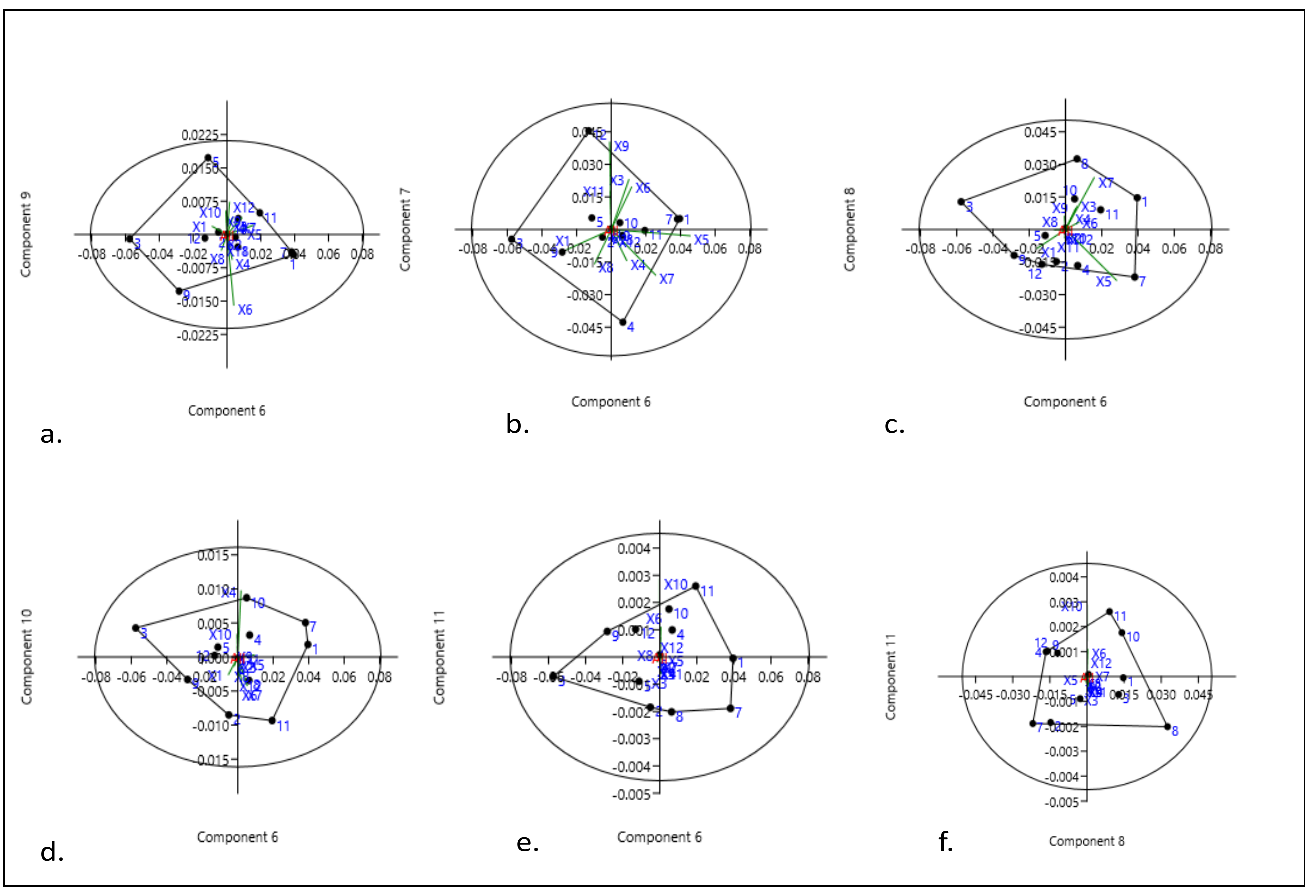

Figure 3a-f. Components (6 and 7 to 9) analysis in the twelve genotypes of basil

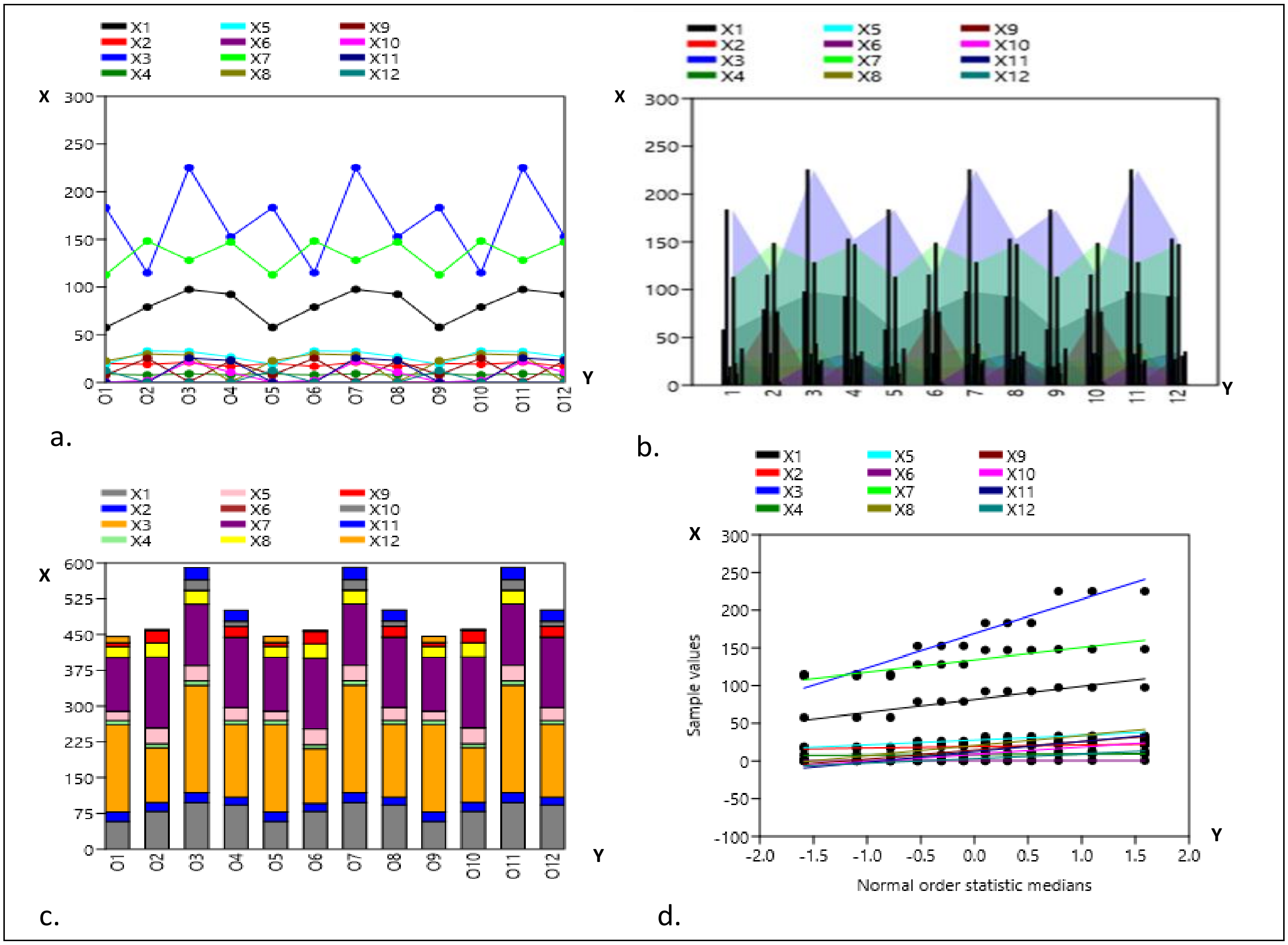

Figure 4a-d. Mean performance and normal order statistic medians (x-axis upper and y-axis horizontal) for the 12 traits of basil

A critical examination of the results reveals some significant findings, such as PC1 to PC11 showed highly variable data values for each PC (Tables 8-9, Figures 1-5a-d), the Principal Component Analysis (PCA) also demonstrated the high genetic diversity in this set of basil materials. Among the twelve traits of the basil, the corresponding highest eigenvalues were 5.121, and the proportion of variances was 42.671 (Tables 8–11). The summary statistics from Principal Component Analysis for the 12 basil traits are shown in Tables 6-9. Qualitative and quantitative features showed significant differences across all traits, confirming earlier findings by Lahiri et al. (2018) that these traits were highly genotype-dependent. Interestingly, plenty of high-production genotypes showed abnormally high levels of linalool and methyl chavicol, indicating the potential for developing specialized cultivars targeted at the pharmaceutical, essential oil, and perfumery industries, which require certain fragrance chemicals. Over the years, G × E analysis has enabled the successful selection of genotypes based on trait performance, which may lead to the identification of divergent paternal lines. Such G × E is necessary to optimize heterosis in successive crosses (Shah et al., 2023, Lal et al., 2023a, Lal et al., 2023b, Lal et al., 2023c, Lal et al., 2023d, Maurya et al., 2022, Rai et al., 2023, Kumar et al., 2024, Singh et al., 2024).

Table 9. Similarity and distance indices for the 12 genotypes related to 12 traits of basil

Parameters	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12
O1	0.00	84.32	71.56	70.05	0.17	84.34	71.66	70.04	0.19	84.29	71.63	69.98
O2	84.32	0.00	120.73	56.03	84.30	2.16	120.78	56.11	84.29	0.13	120.76	56.10
O3	71.56	120.73	0.00	84.37	71.45	120.71	0.16	84.28	71.45	120.65	0.14	84.27
O4	70.05	56.03	84.37	0.00	69.99	55.93	84.42	0.14	69.98	55.99	84.40	0.13
O5	0.17	84.30	71.45	69.99	0.00	84.32	71.55	69.98	0.04	84.27	71.52	69.92
O6	84.34	2.16	120.71	55.93	84.32	0.00	120.77	56.01	84.31	2.22	120.75	56.00

O7	71.66	120.78	0.16	84.42	71.55	120.77	0.00	84.34	71.55	120.71	0.08	84.32
O8	70.04	56.11	84.28	0.14	69.98	56.01	84.34	0.00	69.98	56.06	84.32	0.12
O9	0.19	84.29	71.45	69.98	0.04	84.31	71.55	69.98	0.00	84.26	71.53	69.91
O10	84.29	0.13	120.65	55.99	84.27	2.22	120.71	56.06	84.26	0.00	120.69	56.05
O11	71.63	120.76	0.14	84.40	71.52	120.75	0.08	84.32	71.53	120.69	0.00	84.30
O12	69.98	56.10	84.27	0.13	69.92	56.00	84.32	0.12	69.91	56.05	84.30	0.00

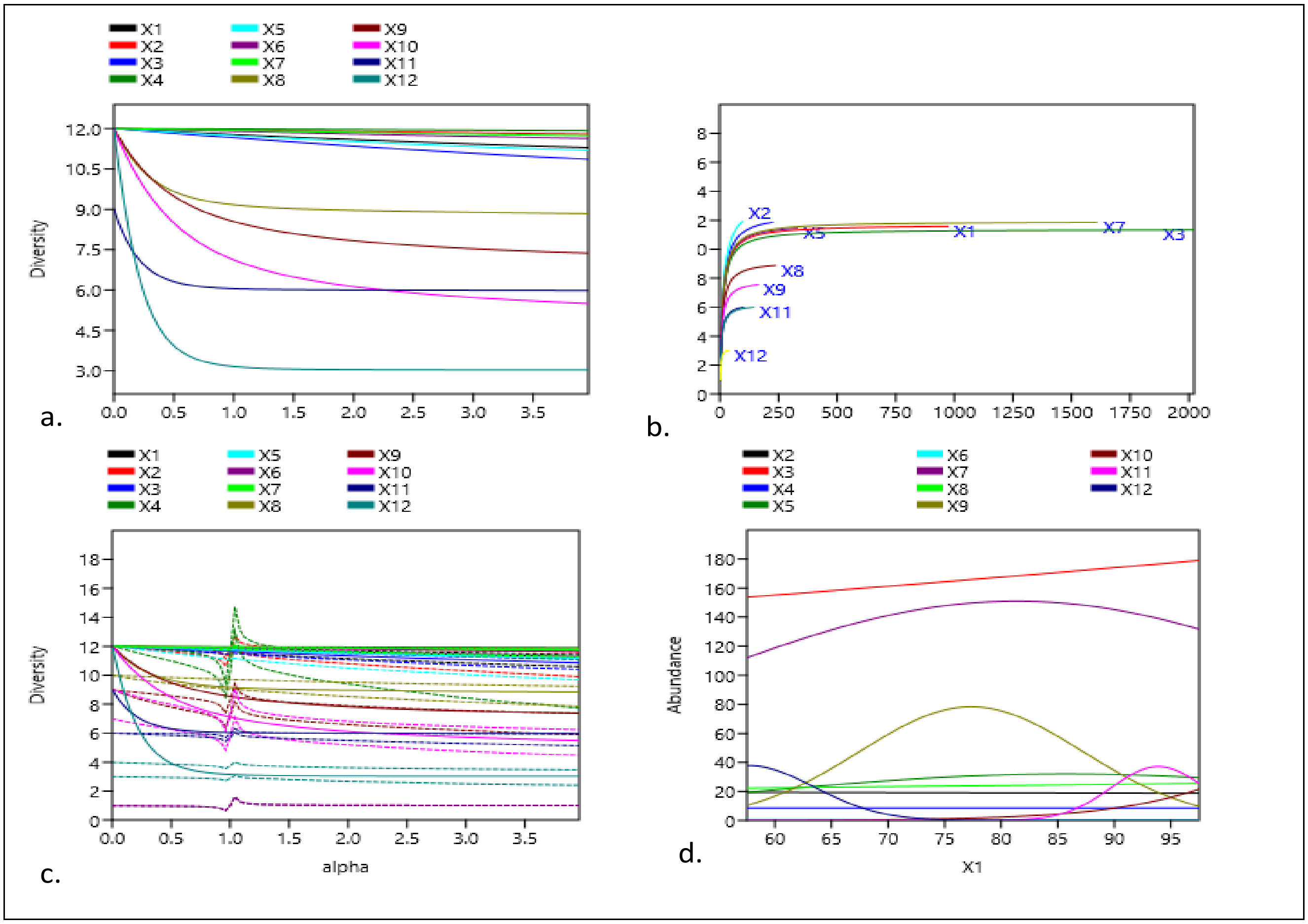

Figure 5a-d. Mean performance and normal order statistic medians for the 12 traits of basil

Table 10. Correlations (Pearson) between different characters in the basil genotypes

Traits	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
X1	1.000	0.685*	0.518	0.820**	0.006	0.021	0.052	0.485	0.990**	0.000	0.000	0.000
X2	-0.131	1.000	0.006	0.000	0.957**	0.209	0.007	0.010	0.000	0.307	0.980**	0.292
X3	0.207	0.737**	1.000	0.000	0.643*	0.463	0.014	0.619*	0.000	0.014	0.071	0.521
X4	-0.074	0.874**	0.942**	1.000	0.442	0.571*	0.000	0.194	0.000	0.136	0.471	0.170
X5	0.741**	-0.017	-0.149	-0.245	1.000	0.000	0.018	0.287	0.556	0.097	0.291	0.000
X6	-0.653*	-0.391	-0.234	-0.182	-0.881**	1.000	0.386	0.058	0.456	0.023	0.245	0.016
X7	0.572*	-0.726**	-0.684*	-0.849**	0.666*	-0.276	1.000	0.311	0.001	0.855**	0.526	0.001
X8	-0.224	0.708**	0.160	0.403	0.335	-0.561	-0.320	1.000	0.210	0.920**	0.158	0.730**
X9	0.000	-0.870**	-0.960**	-0.997**	0.189	0.238	0.809**	-0.390	1.000	0.083	0.352	0.254
X10	0.852**	0.322	0.686*	0.456	0.501	-0.646*	0.059	-0.033	-0.521	1.000	0.000	0.055
X11	0.869**	-0.008	0.538	0.231	0.332	-0.364	0.203	-0.435	-0.295	0.914**	1.000	0.052

X12	-0.898**	0.332	0.206	0.424	-0.898**	0.677*	-0.838**	0.111	-0.358	-0.566	-0.573	1.000

X1 = Plant height (cm); X2 = Branches per plant; X3 = Leaves per plant; X4 = leaf area (cm2); X5 =herb yield (tonnes/ha); X6 = Essential oil content (%); X7 = Essential oil yield (kg/ha); X8 = Methyl chavicol content (%); X9 = Linalool content (%); X10 = Eugenol content (%); X11 = Methyl eugenol content (%).; X12= Camphor (%).

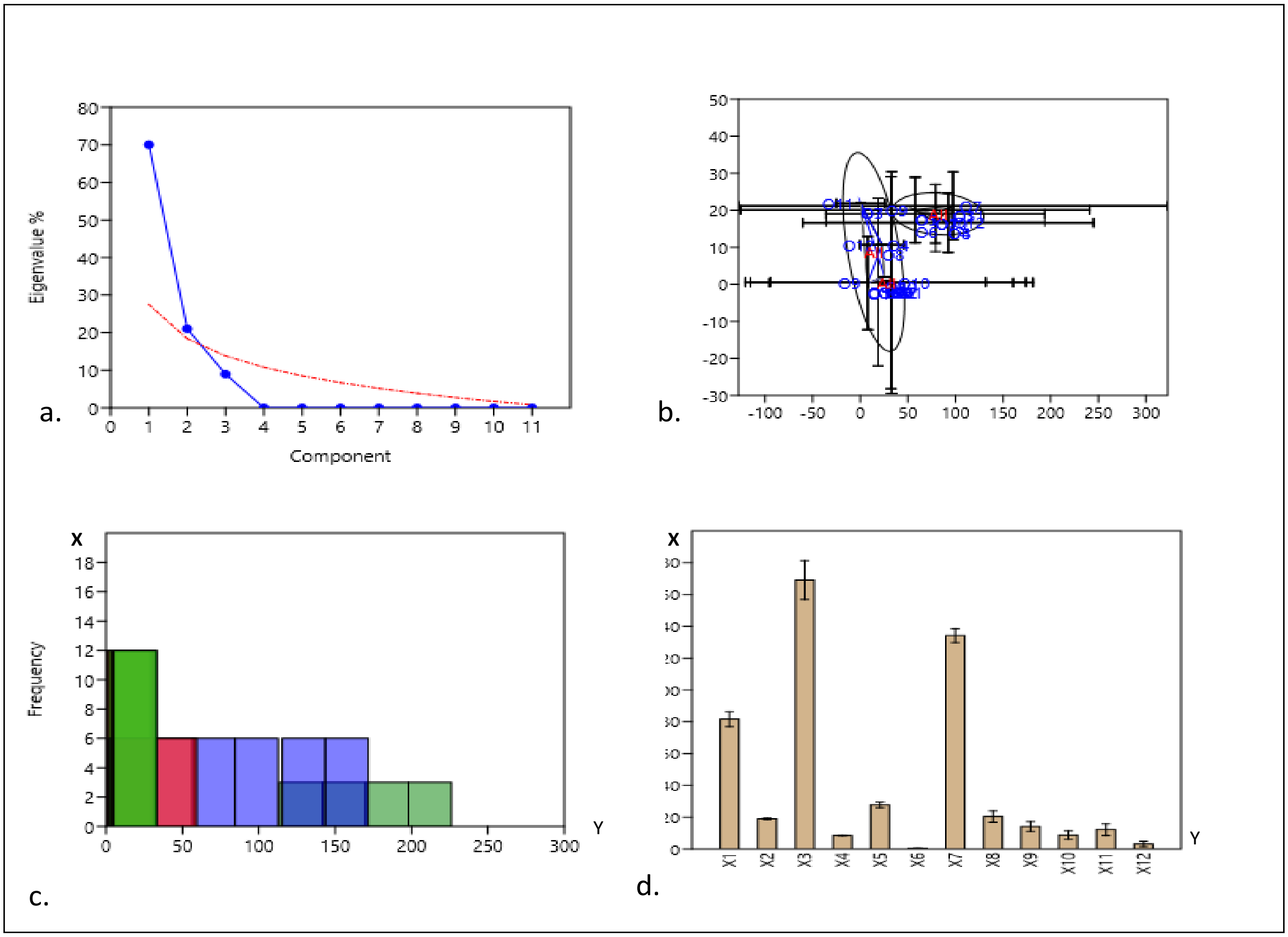

Figure 6a-d. Mean performance, scree plot with Eigen value % for the 12 traits of basil

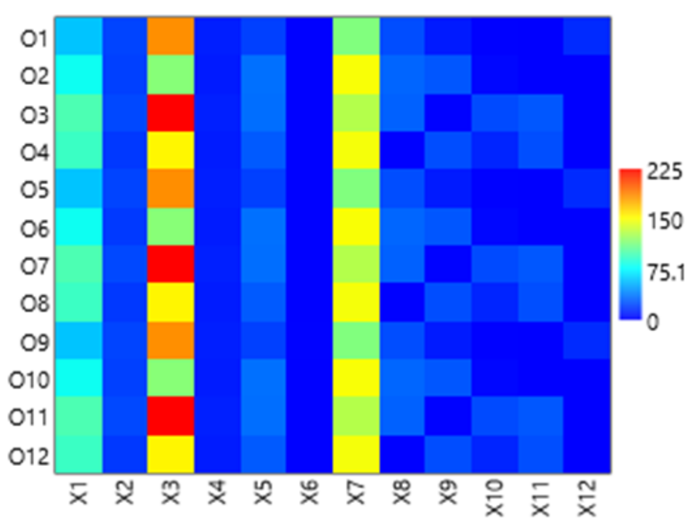

Figure 7. Heat map for the correlations among the 12 traits of basil.

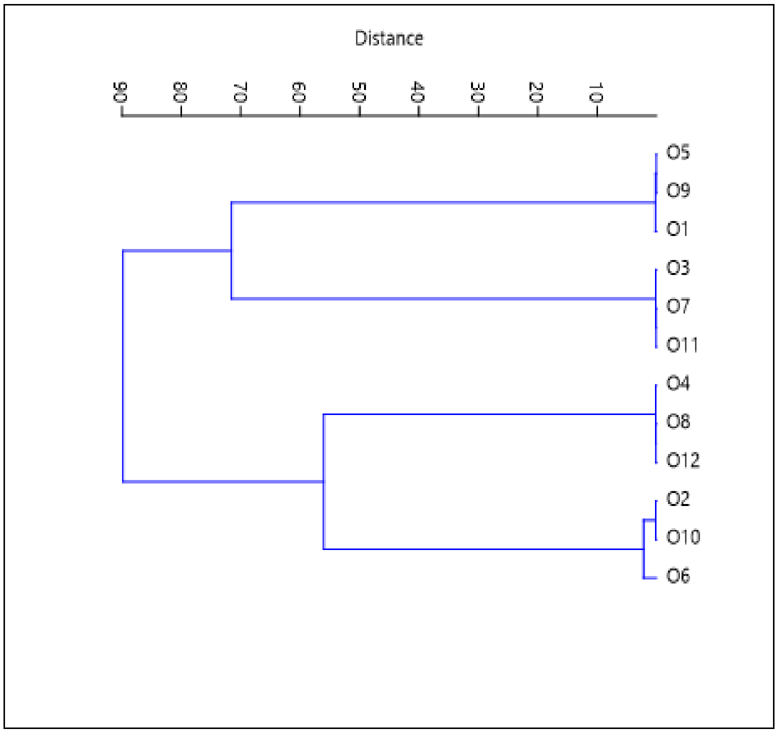

Figure 8. Dendogram for the 12 genotypes for diversity estimation in basil genotypes

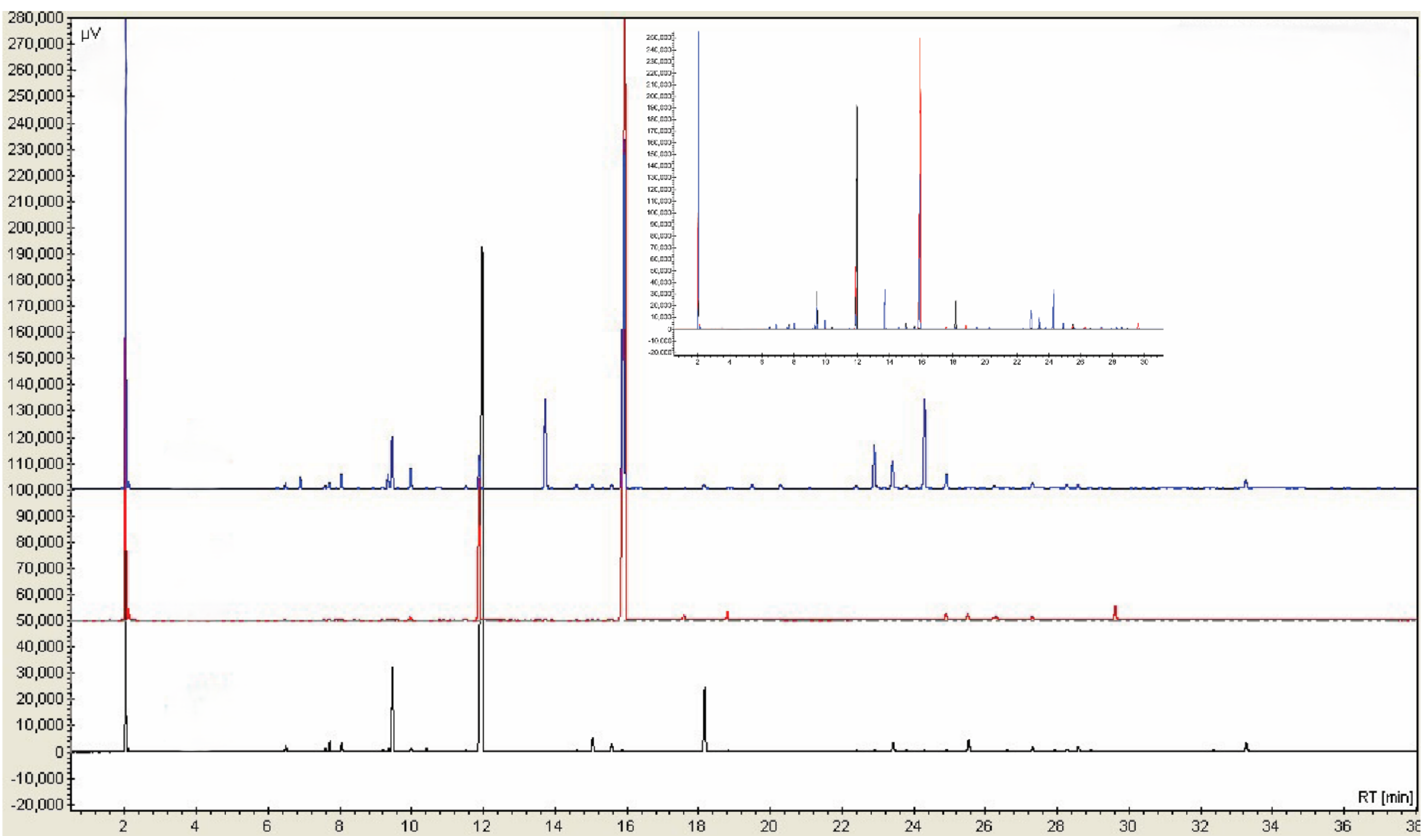

Figure 9. GC/MS choreography of basil lines O1, O2, and O3 essential oils showing separations of aroma compounds.

The type, stability, and degree of genetic variability are also significantly influenced by the connections among the traits. The trait X1 is highly significant and positively correlated with X4 and X9. Similarly, the trait X2 is highly significant and positively correlated with X5 and X11. Likewise, the traits X7 with X10, and X8 with X10 and X12 were positive and highly significantly correlated with each other. However, weak positive and negative correlations between features were also noted (Table 10, Figures 7-10, and 11a-g). Weak positive or negative associations were found in other qualities. Therefore, while choosing various genotypes for hybridization programs, correlations should also be taken into account. This study provides a thorough evaluation of the genetic diversity in the basil accessions with regard to both qualitative qualities and quantitative yield-contributing variables (Table 11). The results show significant variance among the genotypes under investigation, indicating the presence of a broad genetic basis that can be effectively applied in breeding efforts.

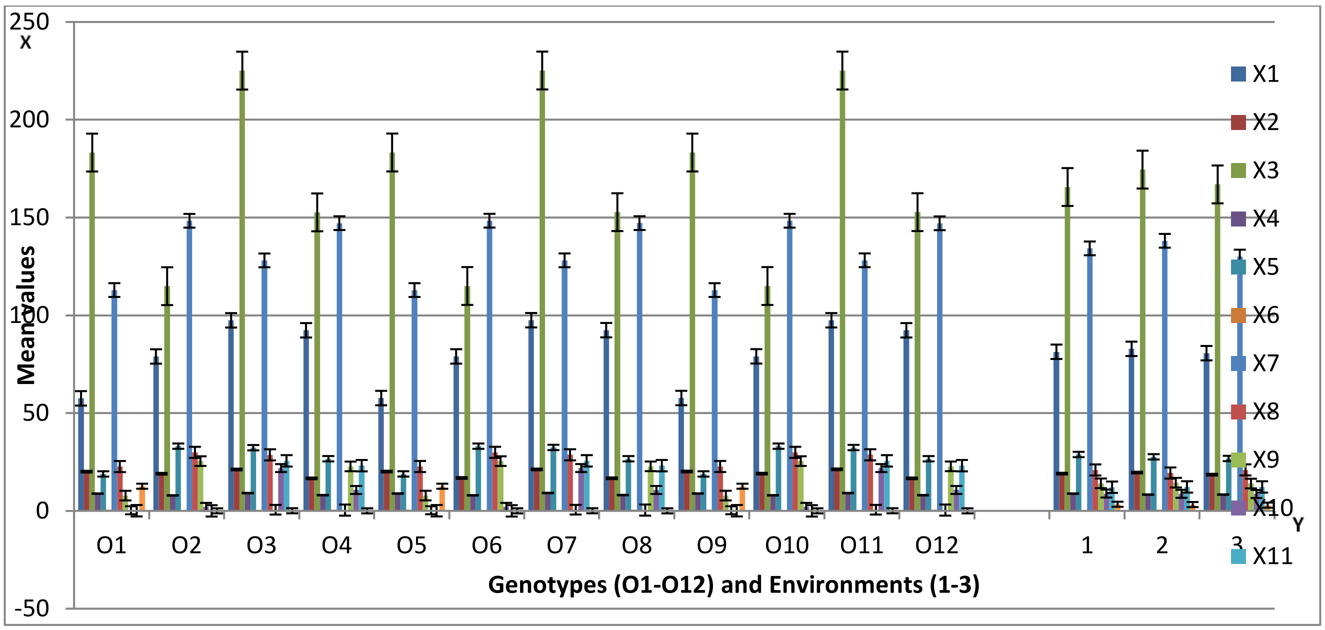

Figure 10. Mean performance of the 12 genotypes over environments in the basil

Table 11. Compositional variability in oil constituents of the most promising breeding lines of *Ocimum* × *basilicum*

Physicochemical Parameters	ISO 11043:1998	RI$_a$	RI$_b$	O1 (CIM-Saumya)	O2 (CIM Surbhi)	O 3	O4	O5	O6	O7	O8	O9
Refractive index @20°C(nD)	1.5100-1.5200			1.5128	1.4634	1.5109	1.5303	1.4746	1.4673	1.4988	1.4766	1.4682
Specific Gravity@20°C(t/t)	0.948-0.970			0.9553	0.8874	0.9697	1.0019	0.9018	0.8892	0.9581	0.9044	0.8880
Flash Point(T$_F$)	(+) 75°C			77.5°C	74.5°C	72.5°C	77.5°C	70.5°C	72.5°C	63.5°C	72.5°C	71.5°C
Constituents												
α-Pinene	-	932	937	t	0.5	0.4	0.3	0.3	0.3	1.3	0.3	0.4
Camphene	-	946	952	t	t	0.9	0.5	0.7	0.7	1.9	0.8	0.9
Sabinene		974	977	t	0.3	0.2	t	0.3	0.3	t	0.2	0.3
β-Pinene	-	976	981	t	0.9	0.6	0.7	0.6	0.5	2.6	0.6	0.7
β-Myrcene	-	988	993	t	0.7	1.2	0.7	0.8	0.7	2.4	0.8	0.9
Limonene	-	1024	1031	t	0.4	1.3	t	1.1	1.0	t	1.2	1.3
1,8-cineole	1.0-3.5 %	1026	1034	t	7.5	4.7	4.4	6.4	6.4	17.1	5.2	5.3
(Z)-β-ocimene		1032	1038	t	t	0.1	t	t	t	t	t	t
(E)-β-ocimene	0.9-2.8 %	1044	1049	0.2	0.3	1.9	1.2	0.6	0.4	3.5	0.6	0.4
γ-Terpinene	-	1054	1061	t	0.3	0.1	t	0.1	0.1	0.2	0.1	0.1
Terpinolene	-	1086	1092	t	0.1	0.2	0.1	0.2	0.2	t	0.2	0.2
Linalool	**0.5-3.0%**	**1095**	**1102**	**10.9**	**71.1**	**3.4**	**2.3**	**59.8**	**71.0**	**5.3**	**56.0**	**66.2**
Camphor	**0.15-0.8 %**	**1141**	**1148**	**t**	**0.1**	**10.0**	**6.0**	**8.0**	**9.2**	**14.1**	**8.4**	**8.9**
Terpinen-4-ol	0.2-0.6%	1174	1180	t	0.2	0.4	0.3	0.5	0.6	0.7	0.6	0.6
α-Terpineol	-	1186	1194	0.1	1.4	0.4	t	t	0.4	t	0.4	0.4
Methyl chavicol	**75.0-87.0 %**	**1195**	1202	**81.3**	**0.8**	**44.9**	**34.7**	**7.8**	**2.6**	**6.1**	**6.6**	**3.1**
Geraniol	-	1249	1257	0.1	7.0	0.4	0.5	0.3	0.2	0.3	0.6	0.3
Bornyl acetate	-	1254	1259	t	t	t	t	t	t	0.9	0.2	0.2
cis-Methyl cinnamate		1305	1308	t	t	0.4	4.7	0.4	0.2	0.5	0.8	0.1
Eugenol	-	1356	1360	0.1	0.1	0.3	0.2	0.2	0.2	0.7	0.2	0.1
Chavibetol	-	**1370**	1373	t	0.2	5.3	1.5	0.7	0.1	11.7	0.4	0.1
***trans*-Methyl cinnamate**		**1384**	1385	0.1	1.0	3.5	31.7	3.0	1.3	4.1	5.5	1.0
β-Elemene	-	1389	1395	t	t	0.4	t	0.3	0.1	0.8	0.4	0.4
Methyl eugenol	0.3-2.5%	1403	1408	t	0.2	10.5	3.9	0.9	0.1	15.4	0.6	0.2
β-Caryophyllene	-	1417	1424	0.6	0.2	1.5	1.0	1.3	0.5	t	1.9	1.7
α-trans bergamotene		1435	1442	0.5	1.4	0.2	0.2	t	t	t	0.2	0.1

α-humulene		1457	1458	0.2	t	0.3	0.3	0.2	0.1	0.6	0.3	0.3
Germacrene D	-	1484	1485	0.4	0.5	0.7	0.5	0.9	0.3	1.3	1.3	1.2
Bicyclogermacrene	-	1500	1501	t	0.1	0.2	T	0.3	0.1	0.7	0.4	0.3
Germacrene A	-	1508	1510	0.1	0.2	0.5	0.5	0.3	0.1	1.5	0.5	0.4
γ-Cadinene	-	1514	1518	t	0.5	0.4	0.3	0.3	0.1	t	0.3	0.3
δ-Cadinene	-	1522	1527	t	0.1	0.1	0.1	0.1	t	0.1	0.1	0.1
Caryophyllene oxide		1582	1582	0.1	t	0.1	0.4	0.1	t	0.4	0.1	0.1
1,10-di-epi-cubenol	-	1618	1619	t	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
Epi-α-cadinol	-	1638	1645	t	1.0	1.0	0.8	0.6	0.5	1.2	0.6	0.5
α-cadinol		1654	1659	t	0.1	0.1	t	t	t	0.3	t	t
				94.7	97.3	96.7	97.9	97.2	98.7	95.9	96.5	97.2

RIa: Reported retention index by Dr. RP Adams, 2017 edition 4.1, RIb: Calculated Retention Index in ELITE-5 capillary columns using a homologous series of n-alkanes (C_7-C_{30} hydrocarbons). tr; trace < 0.1%, nd; not detected.

Figure 11(a-g). a-d: Morphological variability of lines O1, O2, O3, and O4, and in the e-f: inflorescences, and g. flowers of basil

However, given the existence of variants with both high essential oil yield and essential oil profiles, it is possible to concurrently improve both quantitative and qualitative traits, which is a challenge commonly mentioned in basil breeding. Previous research indicates that factors such as temperature, light intensity, and soil nutrient availability can influence the production and quality of essential oils. In essence, this thorough evaluation of genetic diversity offers a strategic basis for creating high-yielding, compound-specific, and locally adapted basil genotypes. In addition to direct cultivation under controlled conditions, identifying genetically diverse and agronomically superior accessions may be useful as breeding parents for the creation of improved cultivars with particular chemical profiles. Performance stability is taken into account as a crucial component of yield testing over year and in various environments. The cultivars selected must take yield and stability into account. The most studied assets of basil exhibited the aforementioned trends. These results are consistent with those of Lal, (2012), Lal et al., (2020), Lal et al., (2022), Sastry et al., (2015), Jakovljević et al., (2023), Kumari et al., (2023), and Kumar et al., (2024).

In a nutshell, different varieties of basil can be categorized as stable variants based on stability data. The genotypes/varieties O-6 and O-10 for essential oil yield and O2, O-6, and O-10 for linalool content (%) were determined to be the most stable and adaptable due to their capacity to withstand a wide variety of environmental conditions throughout time. Thus, in terms of methyl chavicol content (%) and essential oil production, the genotypes/varieties O-6, O-10, and O-2 are not only the most stable but also exhibit good yield performance. Consequently, it is recommended that these cultivars and genotypes be produced profitably.

4. CONCLUSION

In order to identify the genetic variation and factors influencing the production of basil essential oils, a genotype study of twelve distinct genotypes examined genetic variation and twelve economic parameters. These basil genotypes collected from different locations vary morphometrically. The selection of features under study, especially the yield and quality of essential oils, is expected to produce heterotic populations and increase essential oil yield and chemical content. The kind and degree of variation are also greatly influenced by the interactions between the traits. Using PCA and the RBD two-factor design, twelve different basil cultivars were analyzed in this study to determine which ones consistently produced high levels of linalool oil under different conditions and years. It was shown that both PCA and the RBD two-factor design were compatible with the division of genotype and environment into sources of variation.

The RBD two-factor design and Principal component analysis (PCA) revealed that the genotypes/varieties for essential oil yield and O-2, O-6, and O-10 for linalool content (%) had the most adaptability and were the most stable variety due to their capacity to endure a broad range of environmental conditions over time. In light of this, it can be concluded that the genotypes/varieties O-6, OC-8, and OC-10 were the most stable and had good yield performance for the generation of essential oils and linalool content (%). Therefore, it is advised to cultivate these genotypes and cultivars commercially. This basil sample also showed considerable genetic diversity according to PCA, with PC1 through PC12 showing high variable data values for each PC. The PCA also revealed the considerable genetic variety in this set of basil materials. For example, PC1 to PC11 showed extremely varying data values for each PC. The percentage of variance was 42.67, and the matching maximum eigenvalues among the twelve basil traits were 5.12. Heterosis breeding is an effective way to use these genotypes and variability for further genetic advancement.

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Author Contributions

R.K. Lal: Planting, Conceptualization, Investigation. Conceptualization, Statistical analysis, writing of original draft, manuscript preparation, C.S. Chanotiya: Chemical fingerprinting and experimentation.

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Conflict of interest

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

Ethical approval

In this article, as per the plant regulations followed in the Plant Breeding and Genetic Resources Conservation, CSIR-Central Institute of Medicinal and Aromatic Plants, Lucknow 226015, Uttar Pradesh, India; the authors observed the Genotype-environment interactions in Basil. The ethical guidelines for plants & plant materials are followed in the study for plant observation, identification & experimentation.

Informed consent

Not applicable.

Data availability

All data associated with this study will be available upon reasonable request to the corresponding author.

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