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Morpho-biochemical diversity and GC-MS profiling of *Eclipta prostrata* (L.) genotypes

Anite Titus[1], K. S. Sangeetha*[1], P. Anitha[1], P. V. Sindhu[2] and K. Pradheep[3]

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Abstract

Bhringaraj (*Eclipta prostrata*), an annual medicinal herb from the Asteraceae family, is traditionally esteemed for its multifaceted health benefits stemming from its rich array of phytochemicals. This study aimed to evaluate the morphological, yield, and quality diversity of *E. prostrata* genotypes to offer essential insights for enhancing its cultivation and commercialisation, owing to the growing demand for natural products. Significant variability was identified across 35 traits, comprising 16 qualitative and 19 quantitative characters, contributing to morphological, yield, and quality attributes among 25 genotypes. Correlation analysis highlighted a significant positive association between the fresh whole plant yield per plant and morphological attributes, such as plant height, internodal length, leaf length, leaf width, leaf area, and inflorescence diameter. Nine elite genotypes, namely EP 24, EP 7, EP 4, EP 11, EP 12, EP 16, EP 17, EP 20, and EP 15, were discerned through an analysis of yield and associated traits. Significant differences were observed in the phytochemical profiles of elite genotypes, with n-hexadecanoic acid being identified as a key constituent. Cluster analysis grouped the 25 genotypes into five distinct clusters. These findings demonstrate substantial variability among the genotypes and provide valuable genetic resources for crop improvement, commercial cultivation, and phytochemical utilization of *E. prostrata*.

Keywords: *Eclipta prostrata*, genetic diversity, morpho-biochemical characterization, correlation analysis, elite genotype selection

INTRODUCTION

Bhringaraj (*Eclipta prostrata* L.), commonly referred to as false daisy, is a prominent annual medicinal herb from the Asteraceae family, indigenous to Asia and widely naturalised globally (Holm *et al*., 1977), typically found in sunlit, moist environments such as borders of rice field, rivers, lakes, and swamps. This plant, traditionally utilised in Ayurvedic and Chinese herbal medicine, is valued for its hair growth promotion and possesses a multitude of beneficial properties, including hepatoprotection, antioxidation, antivenom, antimicrobial, immunostimulation, antitumor, anti-fibrosis, memory enhancement, and antidiabetic activities, all attributed to its diverse phytochemical constituents (Jahan *et al*., 2014). In addition, the potential to function as a sustainable and eco friendly agent for hair-dyeing (Tripathi and Mondal, 2015) and textile colouration (Alapati and Shaik, 2019) is noteworthy.

Although classified as Least Concern by the IUCN Red List in 2016, heightened market and public interest in natural products necessitates further exploration, conservation, and evaluation of genotypes to mitigate overexploitation and unsustainable harvesting practices, alongside recent research focused on its pharmacological properties, yet lacking in variability assessment. This demands a thorough scientific investigation into the morphological traits and sustainable practices for conserving ecosystems, particularly focusing on genotype variability for commercial cultivation in India, notably in Kerala, where wild habitats serve as key sources for medicinal plants. Therefore, this study aims to analyse the diversity in morphological, yield, and quality characteristics of *E. prostrata* genotypes to provide critical insights for promoting its cultivation and commercialisation.

[1]Department of Plantation, Spices, Medicinal, and Aromatic Crops, College of Agriculture, Kerala Agricultural University, Thrissur 680 656, Kerala, India
[2]College of Agriculture, Padannakkad, Kerala Agricultural University, Kasaragod 671314, Kerala, India
[3]ICAR-NBPGR, Regional Station, Thrissur 680 656, Kerala, India

Corresponding author: K. S. Sangeetha, Department of Plantation, Spices, Medicinal, and Aromatic Crops, College of Agriculture, Kerala Agricultural University, Thrissur 680 656, Kerala, India
*E-Mail: sangeetha.ks@kau.in

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MATERIALS AND METHODS

The experiment was conducted during 2023-24 at the

Table 1. Passport data of *Eclipta prostrata* accessions

Accession code	Accession number	Source	Latitude and Longitude
EP 1	IC632663	Rangath, Middle Andaman, Andaman and Nicobar Islands	12.5074° N, 92.9110° E
EP 2	IC640165	Pattinampakkam, Chennai, Tamil Nadu	13.0299° N, 80.2767° E
EP 3	JPJ/19/mis-8	Bada Enakka, Kamorta, Andaman and Nicobar Islands	8.1740° N, 93.4807° E
EP 4	IC639370	Krishna Nagar, Hut Bay, South Andaman, Andaman and Nicobar Islands	10.8513° N, 92.5726° E
EP 5	IC632661	Sastri Nagar, Great Nicobar, Nicobar, Andaman and Nicobar Islands	6.8072° N, 93.8882° E
EP 6	HJ/19-82	Tipper ghat, Ltabung Lunglei district, Mizoram	22.8423° N, 92.4642° E
EP 7	IC632662	Sastri Nagar, Great Nicobar, Nicobar, Andaman and Nicobar Islands	6.8196° N, 93.8841° E
EP 8	IC639371	Zinganalla, Hut Bay, South Andaman, Andaman and Nicobar Islands	10.7486° N, 92.5544° E
EP 9	AJJPN/19/ Mis-6	Campbell Bay, Great Nicobar, Andaman and Nicobar	7.0081° N, 93.9047° E
EP 10	IC632657	Macachua, Little,Nicobar, Andaman and Nicobar Islands	7.3751° N, 93.7083° E
EP 11	JP/22/Mis-6	Regional Agricultural Research Station, Kumarakom, Kottayam, Kerala	9.6231° N, 76.4292° E
EP 12	EP 12	Vechoor, Kottayam, Kerala	9.6656° N, 76.4189° E
EP 13	EP 13	Kanimangalam Padashekaram, Thrissur, Kerala	10.4806° N, 76.2143° E
EP 14	IC632659	Galathea, Great Nicobar, Nicobar, Andaman and Nicobar Islands	6.8394° N, 93.8485° E
EP 15	IC632656	Campbell Bay, Great Nicobar, Nicobar, Andaman and Nicobar Islands	7.0086° N, 93.9047° E
EP 16	IC632666	Rutland, South Andaman, Andaman and Nicobar Islands	11.4332° N, 92.6497° E
EP 17	IC632658	Afra Bay, Great Nicobar, Nicobar, Andaman and Nicobar Islands	7.1868° N, 93.7348° E
EP 18	EP 18	Thalippadam, Malappuram, Kerala	11.3411° N, 76.3409° E
EP 19	EP 19	Marayoor, Idukki, Kerala	10.2755° N, 77.1631° E
EP 20	IC632665	Sastri Nagar, Great Nicobar, Nicobar, Andaman and Nicobar Islands	6.8333° N, 93.8773° E
EP 21	EP 21	Parassala, Thiruvanathapuram, Kerala	8.3434° N, 77.1531° E
EP 22	IC632664	Barathang, South Andaman, Andaman and Nicobar Islands	12.2240° N, 92.7928° E
EP 23	EP 23	Vayambil, Kodom Belur, Kasaragod, Kerala	12.3729° N, 75.1663° E
EP 24	EP 24	Kareepra, Kollam, Kerala	8.9472° N, 76.7216° E
EP 25	IC632660	Teresa Island, Nancowrie, Nicobar, Andaman and Nicobar Islands	8.2524° N, 93.1315° E

experimental farm of the Department of Plantation, Spices, Medicinal, and Aromatic Crops, College of Agriculture, Vellanikkara, Kerala Agricultural University, Thrissur, located at an elevation of 22 metres above mean sea level and coordinates 10.5477° N and 76.2825° E, with strongly acidic (5.44) laterite soil.

A total of 25 genotypes sourced from different locations (**Table 1**) were used for the study, out of which 18 were sourced from ICAR-NBPGR, Regional Station, Thrissur, and seven local collections from Kerala. Forty-five-day-old seedlings of the genotypes were transplanted to the field following a randomised block design with two replications having a plot size of 1 m^2 at a plant spacing of 20 x 20 cm.

Five plants per replication per genotype were selected and data were recorded at the pre-harvest stage (90 DAT). The data collected were categorised as qualitative, quantitative, and biochemical characters, with qualitative traits encompassing growth characters, stem traits, leaf attributes, inflorescence characters, and seed traits. The quantitative traits encompassed an array of plant morphological attributes, leaf dimensions, inflorescence metrics as well as yield indicators. The biochemical parameters encompassed total alkaloid (%), phenol (mg GAE g^{-1}), and saponin content (%), determined following the methods given by Harborne (1998), Singleton and Rossi (1965), and Obadoni and Ochuko (2001), respectively.

Statistical analysis: The collected quantitative data was subjected for statistical analysis using GRAPES (General R-shiny-based Analysis Platform Empowered by Statistics), as delineated by Gopinath *et al.* (2020). Promising genotypes were identified based on the traits that exhibited significant positive correlations with yield. To ensure equal contribution of each trait irrespective of their measurement scales, the mean values were normalized to a scale of 0 to 1 following the method of Mathew (2003):

$$\text{Transformed value} = (V-Vmin)/(Vmax-Vmin)$$

Where,V: the numerical value attributed to a particular character for a designated genotype, Vmax: the highest value of that character across all genotypes and Vmin: the lowest value of that character among all genotypes.

Equal weights were assigned to all the traits, and the normalized scores were averaged to obtain a selection index, based on which the genotypes were ranked. The superior genotypes identified through the selection index were subjected to GC-MS profiling. Cluster analysis was performed using R software.

RESULTS AND DISCUSSION

Qualitative characters

Marked variations were observed in qualitative traits, with the exception of leaf characteristics (attachment and margin), inflorescence morphology, and seed pigmentation (**Table 2**). The growth forms of *E. prostrata* ranged from erect to semi-erect and prostrate, with 60 per cent of genotypes exhibiting semi-erect growth habit, identified as the most prevalent, followed by erect (36 %). In contrast, only 4 per cent of genotypes exhibited prostrate habit, with genotype EP 23 exemplifying this trait. A notable spreading branching pattern was contrasted with the non-spreading pattern of EP 24. Stem colour serves as a morphological indicator, with pale green being predominant, followed by purple all over, purple tops with pale brown or green stems, and pale brown stem. Additionally, the distribution of trichomes on the stem surface classifies them as sparse, moderate, or dense. All the genotypes exhibited brittleness except for EP 24.

Leaf colour ranged from pale green to green and culminating in dark green, the dominant colour. All genotypes possessed sessile leaves with subentire margins, predominantly elliptic in shape, with lanceolate and elliptic-lanceolate shapes also identified, while linear-lanceolate was exclusive to EP 6. Variations in leaf apex shapes included acuminate, acute, sub-acute, and sub-obtuse, with acute and sub-acute being the most prevalent. In contrast, leaf base shapes varied from attenuate to cuneate, primarily featuring attenuate, acute, and attenuate asymmetric forms, with specific shapes observed in EP 3, EP 13, and EP 6. Leaf pubescence varied from sparse to dense across adaxial and abaxial surfaces, with the densest trichome distribution noted near the midrib on the adaxial surface. No visible variation was observed in inflorescence and seed traits, as all genotypes exhibited a round inflorescence morphology and brown seed pigmentation.

Quantitative characters

Significant variation was observed among the quantitative characters, including plant, leaf, inflorescence, and yield parameters (**Table 3 and 4**). The highest stature and maximum internodal length were recorded in EP 24 and EP 7, whereas EP 23 exhibited the lowest measurements. The maximum number of primary branches per plant was observed in EP 25, closely followed by EP 20, EP 11, and EP 16, while EP 23 exhibited the minimum; conversely, EP 12 demonstrated the highest count of secondary branches, comparable to EP 10 and EP 16, with EP 8 recording the lowest. Leaf dimensions, encompassing length, width, and area, exhibited ranges of 2.88 - 12.54 cm, 0.86 - 2.77 cm, and 1.94 - 18.10 cm^2, with EP 24 presenting superior measurements and minimal values in EP 2, EP 23, EP 21, and EP 5. Among the inflorescence traits examined, the inflorescence count per node exhibited slight fluctuations, with instances of two or three, and it was observed that no two inflorescences on a single node were at identical developmental stages. The peduncle length and inflorescence diameter varied between 0.32 - 4.27 cm and 5.66 - 9.41 mm, respectively, with EP 24 displaying the maximum values and EP 23, EP 21, and EP 2 recording the minimum. The observed variation in peduncle length may be due to its positive and strong correlation with plant height. Days to flower initiation and 50 per cent flowering varied between 4.00 - 28.00 and 10.50 - 41.50 days, respectively. Delayed flowering is generally considered advantageous, as early flowering in annual plants may limit resource accumulation due to reduced nitrogen uptake during the reproductive phase and a decline in foliar photosynthesis associated with monocarpic senescence. Consequently, limited resource availability may result in a trade-off between early flowering and reproductive fitness, whereas delayed flowering allows for greater vegetative growth and biomass accumulation before the onset of reproduction (Wingler and Soualiou, 2025).

Considerable differences were evident in yield metrics, comprising fresh and dry biomass yield per plant. EP 16, EP 24, and EP 17 exhibited superior yields of fresh biomass, in contrast to the inferior performance of EP 22, EP 23, and EP 21. Additionally, EP 24 and EP 16 achieved the highest dry yields, whereas EP 23, EP 21, and EP 22 recorded the lowest. Variations in morphological traits, such as plant height, primary and secondary branch count, node count, internodal length, leaf dimensions, and time to first flowering, likely contributed to the observed differences in biomass yield. Consequently, EP 15, EP 6, and EP 14 demonstrated a more significant dry recovery percentage compared to the lower values in EP 23 and EP 20.

The observed variability in both qualitative and quantitative morphological characters of the *E. prostrata* genotypes suggests a strong underlying genetic basis, further shaped by environmental interactions. Differences in growth habit across genotypes indicate the influence of genetic mechanisms, potentially comparable to those reported in flax (Qi *et al.,* 2022). The diverse variations in stem colour act as a tool for distinguishing genotypes. Similar stem pigmentation variability has been reported in African marigold (Pramila *et al.*, 2011). Comparable findings on the diversity of leaf pigmentation were noted in 16 Indian accessions of *Centella asiatica* (Mathur *et al*., 2003) and 17 genotypes of African marigold (Pramila *et al*., 2011).

Table 2. Frequency distribution of qualitative characters among the *Eclipta prostrata* genotypes

Character	Range of expression	Frequency (%)	Genotypes
Growth habit	Erect	36	EP 1, EP 2, EP 6, EP 7, EP 9, EP 11, EP13, EP19, EP24
	Semi-erect	60	EP 3, EP 4, EP 5, EP 8, EP 10, EP 12, EP 14, EP 15, EP 16, EP 17, EP 18, EP 20, EP 21, EP 22, EP 25
	Prostrate	4	EP 23
Branching pattern	Spreading	96	EP 1, EP 2, EP 3, EP 4, EP 5, EP 6, EP 7, EP 8, EP 9, EP 10, EP 11, EP 12, EP 13, EP 14, EP 15, EP 16, EP 17, EP 18, EP 19, EP 20, EP 21, EP 22, EP 23, EP 25
	Non-spreading	4	EP 24
Stem colour	Pale green	28	EP 1, EP 10, EP 14, EP 17, EP 19, EP 21, EP 24
	Purple all over	24	EP 12, EP 15, EP 18, EP 22, EP 23, EP 25
	Purple tops with pale brown stem	24	EP 2, EP 5, EP 6, EP 11, EP 13, EP 20
	Purple tops with green stems	8	EP 3, EP 4
	Pale brown	16	EP 7, EP 8, EP 9, EP16
Stem pubescence	Sparse	12	EP 3, EP 5, EP 18,
	Moderate	68	EP 4, EP 7, EP 9, EP 10, EP 11, EP 12, EP 13, EP 14, EP 15, EP 16, EP 19, EP 20, EP 21, EP 22, EP 23, EP 24, EP 25
	Dense	20	EP 1, EP 2, EP 6, EP 8, EP 17,
Stem brittleness	Brittle	96	EP 1, EP 2, EP 3, EP 4, EP 5, EP 6, EP 7, EP 8, EP 9, EP 10, EP 11, EP 12, EP 13, EP 14, EP 15, EP 16, EP 17, EP 18, EP 19, EP 20, EP 21, EP 22, EP 23, EP 25
	Non-brittle	4	EP 24
Leaf colour	Pale green	12	EP 13, EP 23, EP 24
	Green	24	EP 2, EP 3, EP 5, EP 18, EP 19, EP 25
	Dark green	64	EP 1, EP 4, EP 6, EP 7, EP 8, EP 9, EP 10, EP 11, EP12, EP14, EP 15, EP 16, EP 17, EP 20, EP 21, EP 22
Leaf shape	Lanceolate	24	EP 1, EP 4, EP 5, EP 7, EP 12, EP 24
	Elliptic	48	EP 2, EP 9, EP 11, EP 14, EP 15, EP 16, EP 17, EP 19, EP 21, EP 22, EP 23, EP 25
	Elliptic-lanceolate	24	EP 3, EP 8, EP 10, EP 13, EP 18, EP 20
	Linear-lanceolate	4	EP 6
Leaf apex	Acuminate	24	EP 1, EP 5, EP 6, EP 7, EP 8, EP 24
	Acute	40	EP 4, EP 10, EP 12, EP 13, EP 14, EP 15, EP 17, EP 18, EP 20, EP 25
	Sub-acute	32	EP 2, EP 3, EP 9, EP 11, EP 16, EP 19, EP 21, EP 23
	Sub-obtuse	4	EP 22
	Attenuate	64	EP 1, EP 4, EP 5, EP 7, EP 9, EP 11, EP 12, EP 15, EP 16, EP 17, EP 19, EP 20, EP 21, EP 22, EP 24, EP 25
Leaf base	Attenuate asymmetric	8	EP 10, EP18
	Acute	16	EP 2, EP 8, EP 14, EP 23
	Acute asymmetric	4	EP 3
	Subacute	4	EP 13
	Cuneate	4	EP 6
Leaf margin	Sub-entire	100	EP 1, EP 2, EP 3, EP 4, EP 5, EP 6, EP 7, EP 8, EP 9, EP 10, EP
Leaf attachment	Sessile	100	11, EP 12, EP 13, EP 14, EP 15, EP 16, EP 17, EP 18, EP 19, EP 20, EP 21, EP 22, EP 23, EP 24, EP 25
Adaxial leaf pubescence	Sparse	72	EP 1, EP 2, EP 3, EP 4, EP 5, EP 6, EP 8, EP 9, EP 10, EP 11, EP 13, EP 16, EP 18, EP 19, EP 21, EP 23, EP 24, EP 25
	Moderate	24	EP 7, EP 12, EP 14, EP 15, EP 17, EP 20,
	Dense	4	EP 22
Abaxial leaf pubescence	Sparse	48	EP 1, EP 2, EP 3, EP 4, EP 5, EP 6, EP 8, EP 9, EP 10, EP 11, EP 13, EP 23
	Moderate	40	EP 7, EP 12, EP 14, EP 16, EP 17, EP 18, EP 19, EP 20, EP 21,
	Dense	12	EP 15, EP 22, EP 24
Abaxial leaf pubescence near midrib	Sparse	24	EP 3, EP 4, EP 5, EP 6, EP 8, EP 13
	Moderate	44	EP 1, EP 2, EP 7, EP 9, EP 10, EP 11, EP 18, EP 21, EP 23, EP 25
	Dense	32	EP 12, EP 14, EP 15, EP 16, EP 17, EP 19, EP 22, EP 24
Inflorescence shape	Round	100	EP 1, EP 2, EP 3, EP 4, EP 5, EP 6, EP 7, EP 8, EP 9, EP 10, EP 11, EP 12, EP 13, EP 14, EP 15, EP 16, EP 17, EP 18, EP 19, EP
Seed colour	Brown	100	20, EP 21, EP 22, EP 23, EP 24, EP 25

Table 3. Mean performance of *Eclipta prostrata* genotypes for plant and leaf characters

Genotypes	PH	PB	SB	NP	IL	LL	LW	LA
EP 1	55.50^{bcd}	10.30^{fghij}	11.30^{hijk}	67.30^{efgh}	7.84^{bc}	6.28^{ef}	1.62^{cd}	4.56^{hij}
EP 2	37.35^{kl}	11.20^{defg}	12.20^{hij}	57.60^{hij}	4.22^{lm}	2.88^{m}	0.90^{ij}	2.23^{no}
EP 3	46.46^{efghij}	11.70^{cdef}	13.60^{ghi}	62.00^{ghi}	6.14^{fghij}	4.76^{jkl}	1.27^{fgh}	4.36^{ijk}
EP 4	51.40^{bcdef}	12.30^{bcde}	22.30^{bcde}	77.80^{de}	6.90^{def}	6.24^{ef}	1.30^{fg}	4.54^{hij}
EP 5	47.21^{efghij}	9.30^{ijklm}	9.62^{hijkl}	81.30^{cd}	5.63^{ijk}	4.53^{kl}	0.95^{ij}	3.19^{lmn}
EP 6	42.51^{ghijkl}	13.10^{bc}	8.00^{jkl}	97.00^{ab}	5.75^{hijk}	5.74^{efgh}	1.27^{fgh}	5.27^{ghi}
EP 7	74.30^{a}	8.20^{lm}	17.97^{efg}	91.50^{bc}	10.16^{a}	10.15^{b}	2.20^{b}	14.62^{b}
EP 8	44.85^{fghijk}	10.75^{efghi}	4.90^{l}	52.90^{ij}	4.90^{kl}	4.37^{l}	1.23^{gh}	2.56^{mno}
EP 9	44.40^{fghijk}	10.75^{efghi}	14.03^{fgh}	67.60^{efgh}	6.82^{defg}	6.40^{ef}	1.38^{efg}	4.36^{ijk}
EP 10	48.77^{cdefgh}	8.90^{jklm}	27.04^{ab}	62.75^{ghi}	6.69^{defg}	5.02^{hijkl}	1.43^{defg}	6.98^{e}
EP 11	53.57^{bcde}	13.40^{ab}	11.72^{hij}	65.90^{fgh}	7.14^{cd}	6.59^{de}	1.74^{c}	9.34^{d}
EP 12	49.77^{cdefg}	10.20^{fghijk}	28.08^{a}	78.57^{de}	7.2^{cd}	7.47^{cd}	1.63^{cd}	11.37^{c}
EP 13	44.84^{fghijk}	12.50^{bcd}	9.07^{hijkl}	59.00^{hij}	6.56^{defgh}	5.53^{fghij}	1.08^{hi}	4.03^{jkl}
EP 14	51.21^{bcdef}	8.60^{klm}	10.00^{hijkl}	54.50^{ij}	6.71^{defg}	5.53^{fghij}	1.43^{defg}	5.25^{ghi}
EP 15	57.36^{b}	11.00^{defgh}	12.65^{hij}	58.50^{hij}	8.44^{b}	5.18^{hijkl}	1.37^{efg}	5.55^{gh}
EP 16	51.65^{bcdef}	13.30^{abc}	26.92^{ab}	79.90^{d}	7.88^{bc}	5.28^{ghijk}	1.53^{de}	5.28^{ghi}
EP 17	48.15^{defghi}	9.90^{ghijk}	7.90^{jkl}	72.20^{defg}	7.05^{cde}	5.68^{fghi}	1.32^{fg}	4.80^{ghij}
EP 18	40.40^{jkl}	7.70^{mn}	26.42^{abc}	48.23^{j}	6.40^{defghi}	4.61^{kl}	1.28^{fgh}	4.34^{ijk}
EP 19	40.78^{ijkl}	9.40^{hijkl}	6.50^{kl}	36.40^{k}	5.99^{ghij}	5.61^{fghij}	1.47^{def}	4.61^{hi}
EP 20	55.74^{bc}	13.50^{ab}	23.63^{abcd}	103.90^{a}	7.13^{cd}	7.65^{c}	2.01^{b}	6.71^{ef}
EP 21	36.21^{l}	12.50^{bcd}	8.37^{jkl}	52.40^{ij}	5.52^{jk}	4.79^{ijkl}	0.86^{j}	3.04^{lmn}
EP 22	48.98^{cdefgh}	8.80^{jklm}	21.70^{cde}	49.10^{j}	6.46^{defghi}	4.84^{hijkl}	1.27^{fgh}	3.52^{klm}
EP 23	22.63^{m}	6.50^{n}	8.67^{ijkl}	23.00^{l}	3.95^{m}	2.94^{m}	0.97^{ij}	1.94^{o}
EP 24	75.90^{a}	8.00^{lmn}	19.00^{def}	56.80^{hij}	10.70^{a}	12.54^{a}	2.77^{a}	18.10^{a}
EP 25	42.03^{hijkl}	14.80^{a}	18.13^{efg}	75.50^{def}	6.22^{efghij}	6.13^{efg}	1.54^{cde}	5.71^{fg}
Mean	**48.48**	**10.67**	**15.19**	**65.27**	**6.74**	**5.87**	**1.43**	**5.85**
SE (m)	**2.60**	**0.56**	**1.78**	**3.88**	**0.30**	**0.31**	**0.07**	**0.35**
CD	**7.59**	**1.63**	**5.19**	**11.32**	**0.88**	**0.90**	**0.20**	**1.02**

P-value < 0.05: PH-plant height (cm), PB-number of primary branches per plant, SB-number of secondary branches per plant, NP-number of nodes per plant, IL-internodal length (cm), LL-leaf length (cm), LW-leaf width (cm), LA-leaf area (cm^2)

Significant differences observed in plant traits may be likely attributable to the interplay of genetic parameters, environmental influences, and adaptive responses to ecological contexts. Variations in leaf dimensions might be potentially attributable to genetic diversity, environmental influences, phenotypic plasticity, nutrient acquisition, and physiological factors. Similarly, significant differences in leaf dimensions were detected among 17 genotypes of African marigold (Pramila *et al*., 2011). Comparable results were noted in the fresh and dry biomass weight per plant upon the assessment of 14 *Bacopa monnieri* accessions sourced from various regions in India (Bansal *et al*., 2016).

Biochemical characters

Significant differences in biochemical constituents, including total alkaloids, phenol, and saponin (**Table 5**), are likely attributable to genotype quality and may arise from genetic and environmental factors. The highest alkaloid content was recorded in EP 24, succeeded by EP 7 and EP 23, whereas EP 3 had minimal content, trailed by EP 4 and EP 5. The highest levels of phenolic compounds were identified with maximum values in EP 20, succeeded by EP 6 and EP 16, whereas EP 21 exhibited the lowest concentrations. The highest saponin content was recorded in EP 6, closely resembling levels in EP 2, EP 1, and EP 7, while EP 12 exhibited the lowest concentration, akin to EP 13, EP 22, and EP 25. Alkaloids are crucial for antibacterial (Gurrapu and Mamidala, 2017) and analgesic (Sawant *et al*., 2004) functions. The high levels of phenolic compounds serve as antioxidants against oxidative stress from reactive oxygen species (ROS) and free radicals. The saponins exhibit antimicrobial properties (Khanna and Kannabiran, 2008).

Table 4. Mean performance of *Eclipta prostrata* genotypes for inflorescence and yield parameters

Genotypes	IN	PL	ID	DF	DH	FBP	DBP	DR
EP 1	2.00^{c}	2.52^{cd}	7.96^{defg}	13.00^{f}	23.00^{efg}	37.75^{fghi}	7.64^{ijk}	20.23^{g}
EP 2	2.00^{c}	0.32^{p}	6.56^{k}	13.50^{f}	18.50^{ij}	29.00^{ghij}	5.68^{jkl}	19.73^{g}
EP 3	2.50^{b}	1.36^{ijk}	7.18^{ij}	16.00^{ef}	22.00^{efghi}	47.00^{def}	12.49^{gh}	26.44^{bcd}
EP 4	2.00^{c}	1.98^{fg}	7.79^{efg}	9.00^{g}	19.50^{ghij}	88.75^{b}	18.80^{de}	21.17^{efg}
EP 5	2.00^{c}	2.69^{bc}	7.18^{ij}	4.00^{h}	10.50$_{k}$	31.00^{fghij}	7.18^{ijk}	23.16^{defg}
EP 6	2.00^{c}	0.66^{no}	7.33^{hij}	9.00^{g}	25.50^{cde}	34.50^{fghij}	11.36^{ghi}	32.89^{a}
EP 7	2.00c	2.11^{efg}	8.91^{b}	19.00^{cde}	27.00^{bcd}	60.00^{cd}	15.08^{efg}	25.15^{cdef}
EP 8	2.00^{c}	1.43^{ij}	8.31^{cd}	8.50^{g}	19.00^{hij}	67.00^{c}	17.82^{def}	26.58^{bcd}
EP 9	2.70^{a}	2.86^{b}	8.41^{c}	19.00^{cde}	22.00^{efghi}	26.00^{hij}	7.09^{ijk}	27.27^{bcd}
EP 10	2.00^{c}	2.10^{efg}	8.19^{cde}	9.00^{g}	17.50^{j}	46.00^{defg}	9.43^{hij}	20.48^{fg}
EP 11	2.00^{c}	1.88^{gh}	8.07^{cdef}	21.00^{bcd}	25.00^{cde}	90.00^{b}	24.18^{b}	26.85^{bcd}
EP 12	2.00^{c}	1.21^{jkl}	8.41^{c}	24.00^{b}	30.50^{b}	54.84^{cde}	14.25^{fg}	25.93^{bcde}
EP 13	2.00^{c}	2.21^{def}	6.72^{k}	18.50^{cde}	24.50^{cde}	30.00^{fghij}	8.55^{ij}	28.52^{abc}
EP 14	2.00^{c}	1.94^{fg}	8.29^{cd}	13.50^{f}	19.50^{ghij}	25.00^{hij}	8.32^{ij}	33.22^{a}
EP 15	2.00^{c}	1.86^{gh}	7.60^{ghi}	9.50^{g}	19.50^{ghij}	58.00^{cd}	18.96^{d}	32.92^{a}
EP 16	2.00^{c}	1.07^{kl}	7.34^{hij}	19.00^{cde}	23.00^{efg}	112.50^{a}	31.04^{a}	27.58^{bcd}
EP 17	2.00^{c}	1.58^{hi}	8.18^{cde}	9.00^{g}	19.00^{hij}	101.00^{ab}	19.74^{cd}	20.03^{g}
EP 18	2.00^{c}	1.08^{kl}	7.27^{hij}	18.00^{de}	20.00^{fghij}	65.00^{c}	14.97^{fg}	23.36^{defg}
EP 19	2.00^{c}	0.99^{lm}	7.79^{efg}	22.50^{b}	28.00^{bc}	39.00^{efgh}	7.92^{ij}	20.29^{g}
EP 20	2.00^{c}	2.35^{de}	6.56^{k}	19.00^{cde}	30.50^{b}	60.80^{cd}	7.63^{ijk}	12.57^{h}
EP 21	2.00^{c}	0.40^{op}	6.33^{k}	19.00^{cde}	24.50^{cde}	20.75^{ij}	4.11^{kl}	19.74^{g}
EP 22	2.00^{c}	0.72^{mn}	7.17^{j}	18.50^{cde}	23.50^{def}	20.09^{j}	6.06^{jkl}	30.31^{ab}
EP 23	2.00^{c}	0.53^{nop}	5.66^{l}	18.50^{cde}	22.50^{efgh}	22.50^{hij}	2.88^{l}	12.75^{h}
EP 24	2.00^{c}	4.27^{a}	9.41^{a}	28.00^{a}	41.50^{a}	109.50^{a}	31.48^{a}	28.61^{abc}
EP 25	2.00^{c}	2.75^{bc}	7.67^{fgh}	21.50^{bc}	30.00^{b}	91.00^{b}	23.45^{bc}	25.76^{bcde}
Mean	**2.05**	**1.71**	**7.61**	**15.98**	**23.44**	**54.68**	**13.44**	**24.46**
SE (m)	**0.03**	**0.11**	**0.15**	**1.07**	**1.28**	**5.85**	**1.30**	**1.66**
CD	**0.09**	**0.32**	**0.44**	**3.12**	**3.73**	**17.07**	**3.79**	**4.84**

P-value < 0.05: IN-number of inflorescences per node, PL-peduncle length (cm), ID-inflorescence diameter (mm), DF-days to first flowering, DH-days to 50 per cent flowering, FBP-fresh biomass yield (g plant^{-1}), DBP-dry biomass yield (g plant^{-1}), DR-dry recovery (%)

Correlation analysis

The association between morphological and biochemical traits and yield, as analysed through Pearson's correlation coefficient, is presented in **Table 6**. The fresh biomass yield exhibited significant positive correlation with various morphological traits, including plant height, internodal length, leaf length and width, leaf area, and inflorescence diameter, indicating that genotypes with comparatively higher values for these traits tended to produce greater biomass. These findings are consistent with the results of Karuppaiah and Senthil (2010) in African marigold, who reported a significant positive correlation between yield and morphological traits. The alkaloid concentration displayed significant positive correlation with plant height, internodal length, leaf dimensions, and 50 per cent flowering, in contrast to a negative correlation with the number of primary branches. Phenol content demonstrated a significant positive association with the number of nodes per plant, whereas the saponin content showed a significant negative correlation with days to first flowering. These associations indicate that the identified morphological traits may serve as reliable selection criteria for improving biomass yield in breeding programmes, although correlation alone does not establish causal relationships.

Comparative phytochemical composition of elite genotypes

The superior genotypes were identified using a selection index based on the traits that exhibited significant positive correlations with yield. The normalized scores (0-1) of the equally weighted traits were averaged to obtain a selection index for each genotype, and the genotypes were ranked according to their mean index values. Based on this

Table 5. Mean performance of *Eclipta prostrata* genotypes for biochemical characters

Genotypes	Total alkaloid content (%)	Total phenol content (mg GAE g^{-1})	Saponin content (%)
EP 1	2.60^{d}	81.20^{l}	3.13^{a}
EP 2	1.20^{k}	61.87^{o}	3.20^{a}
EP 3	0.60^{m}	131.41^{d}	2.53^{c}
EP 4	1.00^{l}	86.50^{jk}	2.92^{b}
EP 5	1.00^{l}	97.72^{h}	2.90^{b}
EP 6	1.60^{i}	158.54^{b}	3.25^{a}
EP 7	3.60$_{b}$	80.88^{l}	3.12^{a}
EP 8	1.40^{j}	103.56^{g}	2.56^{c}
EP 9	1.20^{k}	121.36^{e}	2.30^{de}
EP 10	2.00^{g}	129.07^{d}	2.15^{ef}
EP 11	3.40^{c}	78.31^{lm}	2.60^{c}
EP 12	1.40^{j}	71.53^{n}	1.20^{j}
EP 13	1.20^{k}	91.41^{i}	1.40^{i}
EP 14	1.40^{j}	88.37^{ij}	2.90^{b}
EP 15	1.40^{j}	107.55^{f}	2.93^{b}
EP 16	1.40^{j}	138.91^{c}	3.10^{a}
EP 17	2.20^{f}	131.87^{d}	1.90^{gh}
EP 18	2.40^{e}	84.63^{k}	2.45^{cd}
EP 19	2.00^{g}	75.50^{m}	2.00^{fg}
EP 20	3.60$_{b}$	180.29^{a}	2.49^{c}
EP 21	1.80^{h}	41.35^{p}	1.90^{gh}
EP 22	3.40^{c}	76.44^{m}	1.40^{i}
EP 23	3.60^{b}	101.00^{g}	1.80^{h}
EP 24	6.20^{a}	130.47^{d}	2.50^{c}
EP 25	1.20^{k}	68.95^{n}	1.50^{i}
Mean	**2.11**	**100.75**	**2.41**
SE (m)	**0.05**	**1.04**	**0.06**
CD	**0.15**	**3.03**	**0.18**

P-value < 0.05

ranking, nine superior genotypes, namely EP24, EP7, EP4, EP11, EP12, EP16, EP17, EP20 and EP15, were identified and subsequently subjected to GC-MS profiling for phytochemical characterization. GC-MS profiling of these elite genotypes revealed a broad spectrum of phytochemical constituents (**Table 7**), that may be associated with their pharmacological properties, with the observed variability in their profiles likely resulting from the combined influence of genetic factors, environmental conditions, and their interactions. n-Hexadecanoic acid was consistently detected in all genotypes and constituted the primary component in seven of the nine, suggesting potential therapeutic importance for rheumatic symptoms owing to its anti-inflammatory properties (Aparna *et al*., 2012). Quinic acid and quinone derivatives were identified as the predominant compounds in EP 11 and EP 24, with quinic acid reported to possess notable therapeutic properties, including antioxidant, antidiabetic, anticancer, antimicrobial, antiviral, anti-nociceptive, and analgesic effects (Benali *et al*., 2024), while quinone derivatives have attracted increasing attention for their potential applications in oncology and the management of neurodegenerative disorders due to their cytoprotective role against oxidative stress (Cores *et al*., 2023). Other major compounds identified included linoleic acid methyl ester, 2-amino-3-pyridol, linolenic acid/alpha-linolenic acid, linoleic acid/linoelaidic acid, 10E,12Z-octadecadienoic acid, loliolide, methyl linoleate/linolenic acid, methyl ester, and phytol. Moreover, several phytochemical constituents were identified in trace amounts. Alpha-linolenic acid is esteemed for its anti-inflammatory and antioxidant capabilities (Wijaya and Linawati, 2024), while linoleic acid and linoelaidic acid are primarily noted for their anti-inflammatory and anticancer activities (Dutta *et al*., 2023). Loliolide is recognized for its neuroprotective and anti-inflammatory attributes (Silva *et al*., 2021).

Table 6. Pearson's correlation coefficient analysis for morphological and biochemical characters with yield

	PH	PB	SB	NP	IL	LL	LW	LA	IN	PL	ID	DF	DH	FBP	AC	PC	SC	DR
PH	1.00																	
PB	-0.06	1.00																
SB	0.31	-0.01	1.00															
NP	0.47*	0.52**	0.31	1.00														
IL	0.93***	-0.09	0.39	0.37	1.00													
LL	0.85***	-0.06	0.29	0.41*	0.87***	1.00												
LW	0.84***	-0.09	0.38	0.34	0.85***	0.93***	1.00											
LA	0.81***	-0.16	0.38	0.32	0.83***	0.93***	0.90***	1.00										
IN	-0.09	0.07	-0.05	0.00	-0.04	-0.02	-0.07	-0.12	1.00									
PL	0.65***	-0.01	0.14	0.29	0.63***	0.69***	0.65***	0.55**	0.17	1.00								
ID	0.72***	-0.19	0.17	0.22	0.69***	0.69***	0.67***	0.69***	0.10	0.59**	1.00							
DF	0.17	-0.01	0.29	-0.18	0.33	0.50*	0.52**	0.51**	0.09	0.13	0.11	1.00						
DH	0.41*	0.11	0.23	0.10	0.51**	0.75***	0.74***	0.70***	-0.07	0.32	0.29	0.83***	1.00					
FBP	0.47*	0.27	0.36	0.31	0.51**	0.47*	0.55**	0.48*	-0.20	0.37	0.45*	0.18	0.34	1.00				
AC	0.47*	-0.40*	0.16	-0.10	0.50*	0.62***	0.70***	0.63***	-0.27	0.32	0.23	0.51*	0.62***	0.25	1.00			
PC	0.22	0.13	0.15	0.45*	0.20	0.20	0.31	0.13	0.23	0.26	0.06	-0.18	0.10	0.27	0.15	1.00		
SC	0.33	0.06	-0.11	0.34	0.20	0.06	0.13	0.05	-0.00	0.08	0.15	-0.44*	-0.28	0.12	-0.05	0.26	1.00	
DR	0.34	0.11	-0.04	0.09	0.33	0.19	0.12	0.22	0.13	0.15	0.44*	-0.02	0.05	0.06	-0.18	-0.00	0.13	1.00

***Correlation is significant at 0.001 level (two-tailed) **Correlation is significant at 0.01 level (two-tailed) *Correlation is significant at 0.05 level (two-tailed) PH-plant height, PB-number of primary branches per plant, SB-number of secondary branches per plant, NP-number of nodes per plant, IL-internodal length, LL-leaf length, LW-leaf width, LA-leaf area, IN-number of inflorescences per node, PL-peduncle length, ID-inflorescence diameter, DF-days to first flowering, DH-days to 50 per cent flowering, FBP-fresh biomass yield, AC-total alkaloid content, PC-total phenol content, SC-saponin content, DR -dry recovery

Table 7. Comparative phytochemical profile of elite genotypes

Chemical constituents	Genotypes								
	EP 24	EP 7	EP 4	EP 11	EP 12	EP 16	EP 17	EP 20	EP 15
n-Hexadecanoic acid/Palmitic acid/ Cetylic acid	17.87	30.63	24.46	4.38	22.22	24.64	21.52	26.97	18.86
6-[[5-(Hydroxymethyl)-2,5,8a-trimethyl-1,4,4a,6,7,8-hexahydronaphthalen-1-yl]methyl]-3-methylidene-7-oxabicyclo[4.1.0]heptane-2								-	30.22
2-Hydroxy-3,5,6-trimethyl benzo-1,4-quinone	28.70	-	-	-	-	-	-	3.21	-
Linoleic acid, methyl ester	-	21.41	-	-	3.56	4.07	8.69	-	9.60
Quinic acid	-	-	-	19.55	-	-	-	-	-
2-Amino-3-pyridol	18.26	-	1.76	-	-	2.70	1.92	-	-
Linolenic acid/alpha.-Linolenic acid	12.59	13.74	15.06	-	17.24	16.56	15.68	12.28	10.42
Linoleic acid/Linoelaidic acid	-	-	16.39	-	11.78	14.88	-	9.97	-
10E,12Z-Octadecadienoic acid	-	-	-	-	-	-	13.22	-	-
Loliolide	11.53	1.96	-	12.58	-	-	-	-	-
Methyl linoleate/Linolenic acid, methyl ester	-	2.39	2.28	-	5.99	4.88	7.41	10.32	6.55
Phytol	-	5.10	6.79	-	11.00	8.44	8.48	12.24	9.16
6-Acetyl-4,4,7-trimethylbicyclo[4.1.0] heptan-2-one	-	0.90	-	10.24	-	-	-	-	-
Hexadecanoic acid, methyl ester/ Methyl hexadecanoate	-	1.43	-	-	4.21	4.25	8.64	5.05	3.84
Pyranone	8.37	-	-	-	-	2.43	0.81	0.87	-
l-Proline, N-propoxycarbonyl-, isobutyl ester	-	-	-	-	3.35	-	-	2.10	8.12
Propenenitrile, 2-(2-benzothiazolyl)-3-(2-methoxyphenyl)-	-	-	7.69	-	-	2.14	4.13	4.75	-
Squalene	-	-	-	-	6.80	1.68	1.59	4.78	3.23
Tetradecanoic acid	-	2.02	5.34	-	2.10	0.98	0.47	1.53	-
Octadecanoic acid	-	2.59	4.59	-	3.79	2.36	1.31	2.23	-
7-Oxabicyclo[4.1.0]heptan-3-ol, 6-(3-hydroxy-1-butenyl)-1,5,5-trimethyl-	0.68	-	5.98	-	-	-	-	-	
Octadecanoic acid	-	2.59	4.59	-	3.79	2.36	1.31	2.23	-
Neophytadiene	-	0.70	-	-	3.62	0.95	-	-	-
Heptadecane	-	-	-	-	2.68	1.54	1.13	0.69	-
Indole	-	0.86	-	2.81	-	-	-	-	-

'-': Not detected

Cluster analysis

Evaluation of 35 traits, comprising 16 qualitative and 19 quantitative attributes across 25 *E. prostrata* genotypes using Gower distance and Ward D^2 clustering classified the genotypes into five distinct clusters (**Fig. 1**). Cluster II exhibited the highest number of accessions, comprising 12 genotypes (EP20, EP10, EP18, EP19, EP21, EP12, EP25, EP22, EP16, EP17, EP14, and EP15), followed by cluster III (EP6, EP13, EP8, EP3, EP4, and EP5), whereas clusters I (EP24), IV (EP2 and EP23) and V (EP9, EP11, EP1, and EP7) contained comparatively fewer genotypes, respectively. The single genotype in cluster I was characterized by tall plants, delayed flowering, higher biomass yield, maximum dry recovery, and the highest alkaloid content. Clusters I to V exhibited a high degree of divergence on a scale of 0.6, with cluster I demonstrating the greatest divergence from other genotypes, attributable to its distinctive qualitative and quantitative traits. The distribution of the 25 genotypes into five clusters indicated considerable variability for yield and associated morphological and biochemical traits. The inter-cluster distances ranged from 0.29 (clusters V and

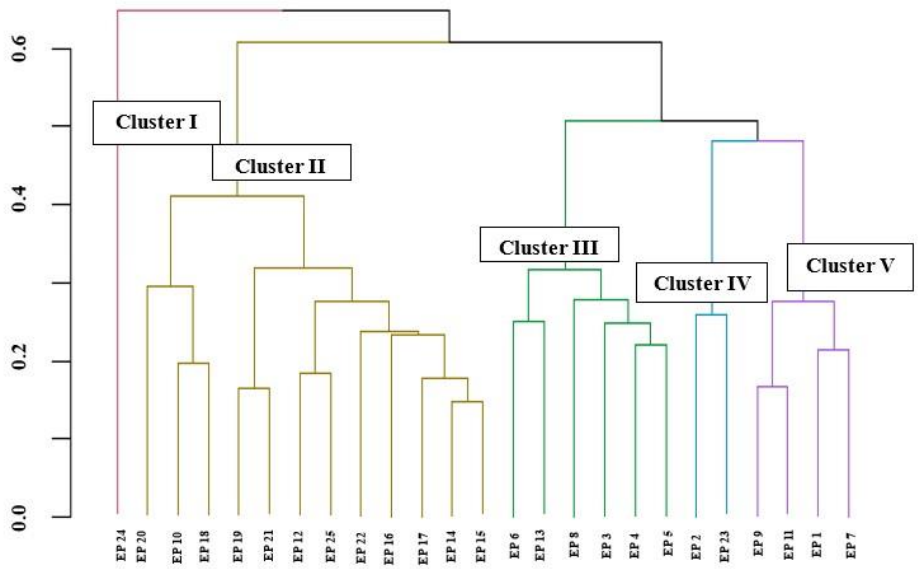

Fig. 1. Dendrogram for Gower distance and Ward D² clustering

II) to 0.63 (clusters IV and I), with the greatest divergence observed between clusters IV and I (0.63), followed by clusters III and I (0.55) (**Table 8**). The greater inter-cluster distances indicate higher genetic divergence among these cluster pairs, suggesting their potential utility as parents in crop improvement programmes. The intra-cluster distances varied from 0.00 (cluster I) to 0.26 (clusters III and IV). The highest intra-cluster distance was recorded in clusters III and IV, followed by cluster II (0.25) and cluster V (0.22), indicating relatively greater variability among the genotypes within these clusters. In contrast, the zero intra-cluster distance in cluster I reflected the presence of a single, distinct genotype. Similar observations were reported by Kumar *et al.* (2021) in ashwagandha, wherein 16 genotypes were grouped into five distinct clusters based on agro-morphological and yield traits, indicating considerable genetic diversity among the genotypes.

Cluster mean values for the 16 quantitative traits are represented in **Table 9**. Distinct differences in cluster means were observed among the five clusters, indicating considerable variability among the *E. prostrata* genotypes. Cluster I recorded the highest mean values for plant height (75.90 cm), number of secondary branches per plant (19.00), internodal length (10.70 cm), leaf length (12.54 cm), leaf width (2.77 cm), leaf area (18.10 cm²), peduncle length (4.27 cm), inflorescence diameter (9.41 mm), days to first flowering (28.00), days to 50 per cent flowering (41.50), fresh biomass yield (109.50 g plant^{-1}), dry biomass yield (31.48 g plant^{-1}), dry recovery (28.61%), total alkaloid content (6.20%), and total phenol content (130.47 mg GAE g^{-1}), indicating the superiority of this cluster for biomass production and phytochemical accumulation. In contrast, cluster IV recorded the lowest mean values for most of the growth and yield traits, including plant height (29.99 cm), leaf dimensions, peduncle length, inflorescence diameter, fresh biomass yield (25.75 g plant^{-1}), dry biomass yield (4.28 g plant^{-1}), dry recovery (16.24%), and total phenol content (81.44 mg GAE g^{-1}). Cluster III exhibited the highest number of primary branches (11.61), whereas cluster V recorded the highest number of nodes per plant (73.08), inflorescences per node (2.18), and saponin content (2.79%). The higher cluster means for biomass yield, delayed flowering and phytochemical traits observed in cluster I suggest that the genotype belonging to this cluster may serve as a valuable donor parent for the simultaneous improvement of yield and quality traits. The variations in morphological, biochemical, yield and phytochemical composition of genotypes may be associated with the genetic factors as well as their interactions with environmental factors,

Table 8. Average intra and inter cluster distance among the five clusters in 25 genotypes of *Eclipta prostrata*

	Cluster V	Cluster IV	Cluster III	Cluster II	Cluster I
Cluster V	**0.22**	0.34	0.31	0.29	0.42
Cluster IV	0.34	**0.26**	0.35	0.36	0.63
Cluster III	0.31	0.35	**0.26**	0.32	0.55
Cluster II	0.29	0.36	0.32	**0.25**	0.50
Cluster I	0.42	0.63	0.55	0.50	**0.00**

Diagonal values represent the intra cluster distance

Table 9. Cluster means for quantitative traits of *Eclipta prostrata* genotypes

Traits	Cluster I	Cluster II	Cluster III	Cluster IV	Cluster V
Plant height (cm)	75.90	47.59	46.21	29.99	56.94
Number of primary branches per plant	8.00	10.72	11.61	8.85	10.66
Number of secondary branches per plant	19.00	18.11	11.25	10.44	13.76
Number of nodes per plant	56.80	64.33	71.67	40.30	73.08
Internodal length (cm)	10.70	6.81	5.98	4.09	7.99
Leaf length (cm)	12.54	5.65	5.20	2.91	7.36
Leaf width (cm)	2.77	1.43	1.18	0.94	1.74
Leaf area (cm^2)	18.10	5.60	3.99	2.09	8.22
Number of inflorescences per node	2.00	2.00	2.08	2.00	2.18
Peduncle length (cm)	4.27	1.50	1.72	0.43	2.34
Inflorescence diameter (mm)	9.41	7.57	7.42	6.11	8.34
Days to first flowering	28.00	16.88	10.83	16.00	18.00
Days to 50 per cent flowering	41.50	23.79	20.17	20.50	24.25
Fresh biomass yield (g $plant^{-1}$)	109.50	57.83	49.71	25.75	53.44
Dry biomass yield (g $plant^{-1}$)	31.48	13.82	12.70	4.28	13.50
Dry recovery (%)	28.61	24.35	26.46	16.24	24.88
Total alkaloid content (%)	6.20	2.02	1.13	2.40	2.70
Total phenol content (mg GAE g^{-1})	130.47	99.54	111.52	81.44	90.44
Saponin content (%)	2.50	2.16	2.59	2.50	2.79

as cultivation practices and climatic conditions for all the genotypes were uniform. In addition, the location of the collection may also have a significant contribution to the variability. The short duration of the crop, as well as its rapid establishment in moist growing conditions, facilitates commercial cultivation. The morpho-biochemical evaluation of genotypes identified nine elite types for yield and yield correlated traits, with EP 24 sourced from the Kollam district of Kerala, the most promising genotype, with erect and non-spreading growth patterns and other superior characteristics. Other superior genotypes were collected from various locations across the Andaman and Nicobar Islands, with the exception of EP 11 and EP 12, which were obtained from different areas in the Kottayam district of Kerala. In contrast, EP 23, sourced from the Kasaragod district of Kerala, was identified as inferior among genotypes with a prostrate habitat. However, the inverse relationship between biomass yield and saponin content indicates that certain low-yielding genotypes may be valuable sources of high saponin content.

The present study revealed substantial morpho-biochemical diversity among 25 *E. prostrata* genotypes, indicating considerable genetic variability for economically important traits. Significant positive associations between fresh biomass yield and plant height, internodal length, leaf dimensions, leaf area, and inflorescence diameter suggest that these traits can serve as effective selection criteria in breeding programmes aimed at improving biomass yield. The selection index identified nine elite genotypes (EP24, EP7, EP4, EP11, EP12, EP16, EP17, EP20, and EP15), with EP24 emerging as the most promising genotype owing to its superior growth, biomass yield, alkaloid content, and favourable phytochemical profile. Cluster analysis further revealed genetically divergent groups that could be exploited as potential parental lines in crop improvement programmes to broaden the genetic base and develop improved cultivars. The identified elite genotypes provide valuable genetic resources for crop improvement, large-scale cultivation, and the commercial production of high quality raw material for the pharmaceutical, nutraceutical, and herbal industries. Future multi location evaluations and molecular characterization will further validate the stability and breeding potential of these genotypes.

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