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MORPHOLOGICAL, BIOCHEMICAL, AND AGRONOMIC TRAITS OF SELECTED *Origanum majorana* L. CLONES

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ABSTRACT

Origanum majorana L. is known for its essential oil yield (EOY) and herbs usage worldwide which contain several secondary metabolites and possess pharmaceutical, medicinal, and culinary properties. There have been a lot of developments in plant production, i.e., from generating new varieties to analyze their properties to exploring new and innovative, sustainable methods for their cultivation but *Origanum majorana* L. species got less attention. In this study, *Origanum majorana* L. clones were selected on the basis of morphology and biochemical traits. Fifty clones were selected from 450 Turkish local *Origanum majorana* L. clones on the basis of high growth rate, lush green color and better adaptability in the studied region. Growth parameters were recorded at different phenological stages, while dried shoot samples of *Origanum majorana* L. were used to determine essential oil yield, antioxidant activity and secondary metabolites constituents. The results of the current study showed that among 50 selected clones, 52% of clones were shown to have an erect growth habit with high performance rate as compared to bushy clones that were on average of 48%. The clone ORM025 showed high biomass and ORM016 higher EOY (2.0 mL 100 g^{-1}) while ORM014 showed high antioxidant activity. The high number of secondary compounds were observed from ORM006 and ORM044 (50 compounds) while ORM014 clones produced the lowest (18 constituents only) number of secondary metabolite constituents proving an inverse relationship between EOY and secondary metabolite constituents. Overall, ORM025, ORM016 clones proved high biomass and EOY, ORM014 showed high antioxidant activity and ORM006 and ORM044 produced a high number of compounds proving the efficiency of these genotypes for further breeding programs. The present study focuses on finding the elite clone among fifty which should have properties like high EOY and herbage yield. In future, molecular studies and in vitro studies are needed to check the genetic diversity and reproducibility of these fifty clones.

Keywords: sweet marjoram, clones, morphology, antioxidants, essential oil

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INTRODUCTION

Medicinal plants have long been recognized for their ability to produce a wide range of bioactive compounds with antimicrobial, antiviral, antifungal, and antioxidant properties (Gurib-Fakim 2006; Panda *et al.*, 2025). These natural products are commonly used in the treatment of various illnesses, including gastrointestinal, respiratory, and urinary tract conditions. Additionally, some medicinal plants serve as flavoring agents due to their aromatic properties. Few plant families have medicinal properties which are vital in pharmaceutical culinary properties and Lamiaceae family is one of those. Important plants of this family like lavender, thyme, basil, and Origanum species are well known for their distinguished properties.

Origanum majorana L. commonly known as sweet marjoram, is a medicinal herb belonging to the genus *Origanum* and family Lamiaceae. Within the flora of Türkiye, this genus is represented by 23 species and 6 hybrids, of which 14 are endemic *Origanum majorana* L. is a soft, perennial herb native to North Africa and Southeast Asia, with its natural habitat extending into Southern Europe. It is widely cultivated in Mediterranean countries, including France, Greece, Hungary, the United States, and Egypt (Duman, 2000).

It is a bushy herb that grows 30-80 cm tall with square shaped shrubs like branches and stems (Bina and Rahimi, 2016). It usually grows under mild weather conditions with a temperature range of 24-30˚C. It is cultivated from March to September under sunny and dry conditions in the southern hemisphere. It prefers loamy fertile soil with pH 6-7. The seedling emergence usually occurs within 2-4 weeks after sowing.

This species is mainly known for its essential oil which contains several secondary metabolites with huge

biological activity (Kakouri *et al.,* 2022). These secondary metabolites are usually derived from the aerial parts such as flower, stem, leaves, seeds and aerial parts and consist of amino acids, proteins, carbohydrates, vitamins, phenolic compounds, flavonoids, phenolic acids, saponins and tannins (Anonymous, 2015; Ayari *et al.,* 2013; Bouyahya *et al.,* 2021). The concentration of EOY varies from 1.2-3% depending on geographical locations and climatic conditions of a specific area (Attia *et al.,* 2023). Among all derived secondary metabolites, oxygenated monoterpenes and monoterpenes hydrocarbons are presented in high quantities. The sesquiterpenes, either oxygenated or non-oxygenated, are present in less quantities. The oil obtained from the aerial parts of this plant contains a large amount of terpinene-4-ol, *g*-terpinene and *cis*-sabinene hydrate. While in some studies, the oil is rich in thymol and carvacrol with the less or even absence of terpinene-4-ol (Ragab *et al.,* 2019; Prabu *et al.,* 2020).

The phytochemical obtained from *Origanum majorana* L. varies according to plant part like its flower (1,8-cineole, carvacrol, carvone, camphene, limonene, linalool, myrcene, sabinene and terpenoids) (Ayari *et al.,* 2013; Bouyahya *et al.,* 2021), leaves (terpenoids, terpineol, sesquiterpene, terpenes, phenolic acids phellandrene, sabinene, flavonoids, tannic acid, coumarins, gallic acid, thujene, pinene, borneol, linalool and carvacrol) (Ayari *et al.,* 2013; Calín-Sánchez *et al.,* 2015), stems (thymol, sabinene, linalool, carvacrol methyl ether, α, β- thujene, α- terpineol, αpinene, borneol and camphene) (Prerna and Vasudeva, 2016), seeds (terpenoids, phenolic acids, gallic acid, catechol, ascorbic acid, cinnamic acid, terpineol, sabinene, phellandrene, myrcene, pinene, thymol, linalool and terpinol acetate) (Jan *et al.,* 2018; Xylia *et al.,* 2021) and aerial parts (carvone, phenolic acids, flavonoids, terpenoids, sabinene, camphene, rosmarinic acid, gallic acid, caffeic acid, phellandrene, epicatechin, limonene, thymol and vanillic acid) (Taamalli *et al.,* 2015; Bouyahya *et al.,* 2021).

Morphological traits vary according to geographical location and the presence of secondary metabolites in *Origanum majorana* L. (Attia *et al.,* 2023; Ragab *et al.,* 2019; Prabu *et al.,* 2020). Hence it is important to observe the morphology and biochemical traits of *Origanum majorana* L. according to geographical locations. There are some studies available on its morphology and biochemical traits in different parts of the world, but less literature is available that focuses on morphology and phytochemical characteristics of *Origanum majorana* L. clones in Türkiye. *Origanum majorana* L. is a high-value medicinal and aromatic herb with diverse therapeutic properties that promote its extensive utilization in dietary applications, pharmaceutical formulations, and food processing industries. Recent literature reports emerging breeding programs for *Origanum majorana* L. that explore novel methodologies and advanced techniques for genetic improvement. Climate change has imposed significant challenges affecting both yield and quality parameters of *Origanum majorana* L. with reduced adaptability rendering the species increasingly vulnerable to environmental stressors. Consequently, there is an urgent need for comprehensive studies focused on identifying genotypes with enhanced survival capacity and superior performance in fresh herb yield, dry herb production, and EOY (Jelali, 2011).

The current study aims to select superior clones of *Origanum majorana* L. due to the escalating global demand for *Origanum majorana* L. hence the development of high-yielding clones represents the primary objective of this investigation. The identification and selection of elite genotypes will further contribute to the genetic improvement of *Origanum majorana* L. and support the development of high yielding cultivars with enhanced commercial viability. For the statistical analysis, principal component analysis (PCA) was used in order to reduce the dimensionality and unravel major patterns of variation. PCA is a multivariate technique that reduces a set of measurements taken on the same samples into a smaller number of new variables called principal components (PCs). These components are linear combinations of the original variables chosen to capture as much as possible so that the main patterns in the data are summarized by the first few PCs. PCA applied in many fields like metrology, psychology, biology, chemistry, and engineering (Greenacre *et al*., 2022). Moreover, this study explores relationships of morphological traits and their antioxidant activity among 50 selected clones and provides pathways for future research.

MATERIALS AND METHODS

Hybrid seed, comprising 450 breeding clones of *Origanum majorana* L., was obtained from an open-pollinated population supplied by Prof. Mehmet Arslan, Faculty of Agriculture, Erciyes University, Türkiye who owns these seeds and is working on these hybrid lines of *Origanum majorana* L. clone species. All seed lots were provided directly by the donor institution and are considered authenticated breeding material; no plant material used in this study was collected from natural or wild populations. The hybrid seeds were manually seeded on February 20, 2020, into plastic trays (32-cell seedling trays; each cell 5 cm in diameter and depth) filled with peat substrate (TS1, Klasmann-Deilmann GmbH, Germany). The trays were monitored daily and regularly irrigated to maintain moisture until seedling emergence was achieved.

Once the seedlings reached a height of 8–10 cm, they were transplanted on April 14, 2020, into the

experimental field of the Faculty of Agricultural Sciences and Technologies at Niğde Ömer Halisdemir University, Niğde, Türkiye. Plants were transplanted as a single plant with plant to plant distance of 50 cm and row to row distance of 90 cm, and 450 clones were planted individually. A drip irrigation system was installed in the field, and initial irrigation was applied immediately after planting. Plants were irrigated regularly and maintained using standard cultural practices. Selection of 50 clones among 450 was made on the basis of physical appearance of each plant, and then further parameters were recorded.

At the end of the establishment year, 50 promising clones were selected from the 450 clones on the field. These selected clones were based on their adaptability in the area, high growth rate, leaf shape, flower color, and general plant appearance in 2021 and 2022 growing seasons.

Three bushes of each clone were selected randomly, referring to the number of replication and their morphological, agronomic, and biochemical data were collected during the third growing season, specifically in August–September 2022. The experimental area i.e., Niğde, Türkiye, experiences an inland continental climate characterized by hot, dry summers and cold, snowy winters. Growth conditions such as temperature and relative humidity at the time of data collection during August to September is presented in Table 1.

Table 1: Temperature and relative humidity during data collection

	Temperature (°C)	Relative Humidity (%)
August, 2022	24.59	42.150
September, 2022	18.36	50.727

Source: Niğde Meteorology Station, Niğde, Türkiye

Trait evaluation and Data Collection: Morphological, agronomic, and biochemical data recorded from each selected clone. Agronomic traits were evaluated as following:

Growth Habit, Plant Height and Branch Length and Internode Length and Number of Nodes: Growth habit was recorded visually for each clone and categorized as erect or semi-erect, and scored as 7 and 5, respectively. Plant height was measured from the soil surface to the tip of the tallest shoot from 10 randomly selected tillers from each plant per clone. The longest branch per plant was also measured using a measuring tape. Internode length was determined as the distance between two adjacent nodes on the main stem. The total number of nodes per plant was counted from the soil surface to the apical meristem on the same selected plants.

Leaf size, Number of tillers, Fresh and Dry Herbage Yield: For leaf size analysis three leaves per plant were selected because in each plant there were 15 to 20 stems and major stems were chosen that had young and green leaves. Leaves selection was based on the plant development stage where the plant has young leaves and fully expanded as well. Third or fifth leaf were chosen from top in order to get the perfect sampling material. Three leaves per plant were used to measure leaf area which was calculated by measuring the leaf length (from tip to base) and maximum leaf width perpendicular to the midrib, following the method of Shi *et al.* (2019). The number of tillers originating from the plant base (crown) were counted for each clone. Fresh herbage yield was determined by harvesting five randomly selected tillers 5 cm above ground level and immediately weighing their aerial parts (stems and leaves) using a weight balance (Shimadzu). For dry herbage yield, samples were oven-dried at 60°C for 48 hours before weighing, as described by (Azizi et al., 2009) and (Sönmez, 2019).

Fresh Leaf Color and Dry Herbage Color, Fresh and Dry Leaf Yield, Leaf-to-Stem Ratio (LSR): Leaf and dry herbage color was measured using a Konica Minolta Chroma Meter. Color parameters [L^*, a^*, b^*; where L^* represents lightness, a^* represents green-red chromaticity, and b^* represents blue-yellow chromaticity] recorded, and chroma (C^*) and hue angle (H°) were calculated according to CIE color space (Madeira *et al.,* 2003). Fresh leaves from ten randomly selected tillers were weighed immediately after separation from stems. Dry leaf weight was determined after drying at 60°C to constant weight. LSR was calculated as the ratio of dry leaf weight to dry stem weight per plant. A higher LSR indicates a greater proportion of usable biomass (León et al., 2007).

Essential Oil Extraction, Total Antioxidant Activity: Essential oil was extracted from 100 g of dried aerial biomass per clone using hydro-distillation with a Clevenger-type apparatus, following the method of Wichtl (1971). Essential oil was collected, dried over anhydrous sodium sulfate, and stored at 4°C (Teixeira, 2013). Antioxidant activity was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, with ascorbic acid (40 mg/mL) as the standard (Huang *et al.,* 2006; Lachman *et al.,* 2008). Extracts were prepared by dissolving 0.4 g of lyophilized plant material in 10 mL methanol (99%), shaken for 150 minutes, centrifuged at 6000 rpm for 15 minutes, and filtered. Absorbance was measured at 517 nm using a UV-Vis spectrophotometer.

Antioxidant activity was calculated as percent inhibition according to

(Huang *et al.*,2006; Lachman *et al.*,2008):

Inhibition activity (%) = $[1-(A_{sample} / A_{blank})] \times 100$

Where:

A_{sample}=Absorbance of test sample

A_{blank}= Absorbance of the control(blank)

Total antioxidant activity was expressed as mg ascorbic acid equivalents (AAE) per 100 g dry weight using the standard equation:

$y = 10.244x$ ($R^2 = 0.997$)

where y = % inhibition activity; x = concentration mg AAE/mL

GC-MS Analysis: GC-MS Analysis was performed for 15 best performing clones that were selected on the basis of higher growth rate, morphological traits and greater adaptability observed in the current experiment. Phytochemical composition was analyzed using gas chromatography–mass spectrometry (GC-MS) with a Shimadzu QP2010 system and an InertCap 5MS/Sil capillary column (60 m × 0.25 mm × 0.25 μm). The oven temperature was programmed from 40°C (held for 2 min) to 260°C at 10°C/min. Helium was used as the carrier gas (1.4 mL/min). Electron ionization was performed at 70 eV. Compounds were identified by comparing mass spectra with the WILEY 275.L library (Adams, 2017).

Statistical Analysis: The collected data regarding growth parameter, EOY, and antioxidant activity were analyzed using Statistix software [v8.1, Analytical Software (USA)] software. One-way ANOVA (analysis of variance) was performed to check the significance of data. In case of significant effects of treatments, Tukey's HSD (Honestly Significant Difference) test was used to compare the means at $p \leq 0.05$ (Steel *et al*., 1997). Correlation analysis was performed using SPSS software while Principal component analysis was done using Past software (4.x, Øyvind Hammer (University of Oslo, Norway).

RESULTS

Growth habit was scored based on visually observation of the erect clones given 7 and semi-erect 5, respectively. The analysis results found that among 50 clones, 52% of plants were erect and the rest 48% were semi-erect, which shows a pattern of growth in *Origanum majorana* L. (Figure 1).

Plant height has a significant role in morphology of plants which decides yield and production of herbs and essential oil. The clone ORM022 was a significantly taller one with almost 100 cm plant height and ORM026 was the shortest one with 45 cm height (Figure 2). The average height of clones varied and ranged from 60-80 cm while only a few clones were achieved higher than 80 cm.

The length of the longest branch of the clones also varied. The clone ORM022 was a significantly taller one with almost 35 cm and ORM026 was the shortest one with only 5 cm in length (Figure 3). The average length of the longest branch of clones varied and ranged from 5-25 cm while only a few clones were achieved higher than 35 cm.The length of the internodes of the clones varied significantly. Clone ORM022 had the longest internode length with almost 5.5 cm while the clone ORM006 had the shortest one with less than 2 cm of internode length (Figure 4). The average internode length of clones varied and ranged from 3-4 cm while only a few clones were achieved higher than 5 cm.

The number of nodes produced by each clone differed significantly among all observed clones. Clone ORM028 produced the maximum number of nodes of 35 while the clone ORM015 had the lowest number of nodes (Figure 5). The average number of nodes ranged from 15-20 per plant from each clone.

The leaf size of each *Origanum majorana* L. clone differed significantly among all observed clones. Clone ORM031 produced the maximum leaf size of 75 cm while the clone ORM004 had the lowest leaf size of only 20 cm (Figure 6). The average leaf size ranged from 50-60 cm per plant from each clone.

The number of tillers significantly differed among the clones of *Origanum majorana* L. Clone ORM022 produced significantly the high number of tillers with almost 220 stems per plant followed by ORM008. Clone ORM033 produced the lowest number of tillers per plant of only 45 stems per plant (Figure 7). The average number of tillers from each clone ranged from 50-150 tillers per plant while some clones were able to produce more than 150 tillers per plant.

There was a significant difference in fresh leaf yield of the clones observed in the current study. Clone ORM003 had the highest fresh leaf yield with almost 17 g and ORM012 produced the least fresh leaf yield among all clones (Figure 8). The average fresh leaf yield among all clones varied significantly and ranged from 5-10 g while only a few clones achieved higher than 10 g of fresh leaf yield.

The fresh stem yield significantly differed among the clones of *Origanum majorana* L. Clone ORM004 produced significantly high fresh stem yield of 30 g while clone ORM015 produced the lowest fresh stem yield of only 5 g (Figure 9). The average fresh stem yield from each clone ranged from 5-15 g while only a few clones were able to produce more than 15 g of fresh stem weight.

There was a significant difference in dry leaf yield of the clones observed in the current study. Clone ORM003 had the highest dry leaf yield with almost 9 g and clones ORM011 and ORM012 produced the least dry leaf yield among all clones (Figure 10). The average dry leaf yield among all clones varied significantly and ranged from 2-5 g, while only a few clones achieved higher than 5 g of dry leaf yield.

The dry stem yield significantly differed among the clones of *Origanum majorana* L. Clone ORM005 and ORM007 produced significantly high dry stem yield of 3g while clone ORM015 produced the lowest dry stem

yield of only 0.2 g (Figure 11). The average dry stem yield from each clone ranged from 0.2-1.5 g, while only a few clones were achieved higher than 10 g of fresh leaf yield.

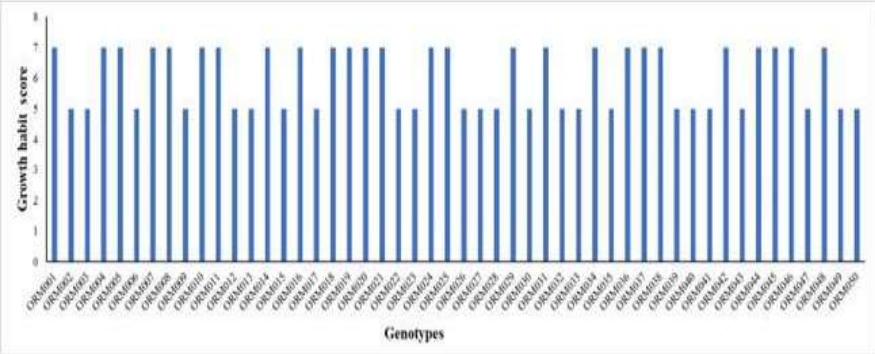

Figure 1: Growth habit scores of 50 *Origanum majorana* clones. Growth habit was visually scored on a standardized scale (5,7), where7 presented erect while 5 semi-erect.

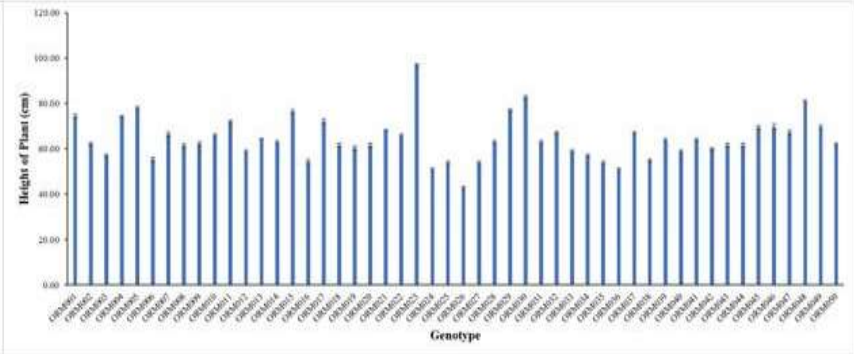

Figure 2: Phenotypic variation in plant height (cm) across 50 *Origanum majorana* clones. Error bars indicate standard error of the mean. The mean values for clones varied significantly according to ANOVA (P≤0.05).

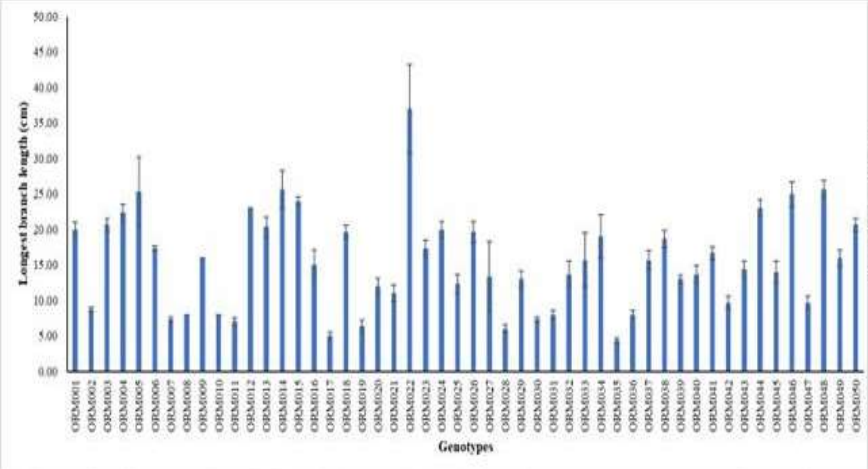

Figure 3: Phenotypic variation in longest branch length among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05). Do not bold the captions of tables and figures.

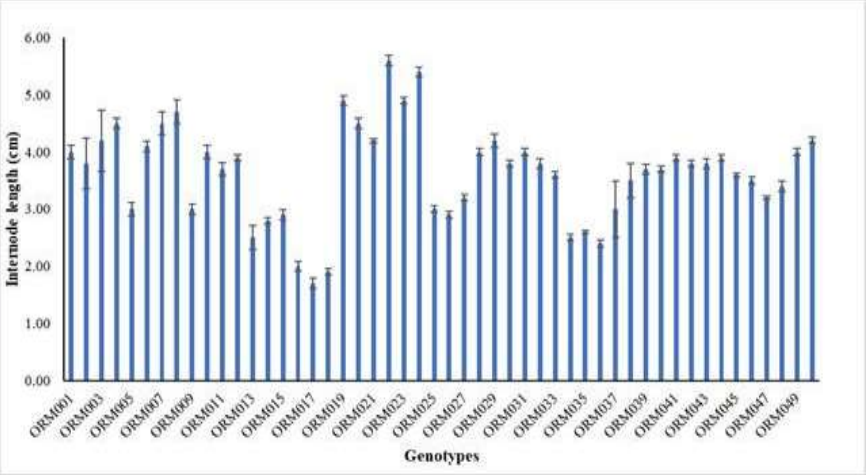

Figure 4: Phenotypic variation in internode length among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05).

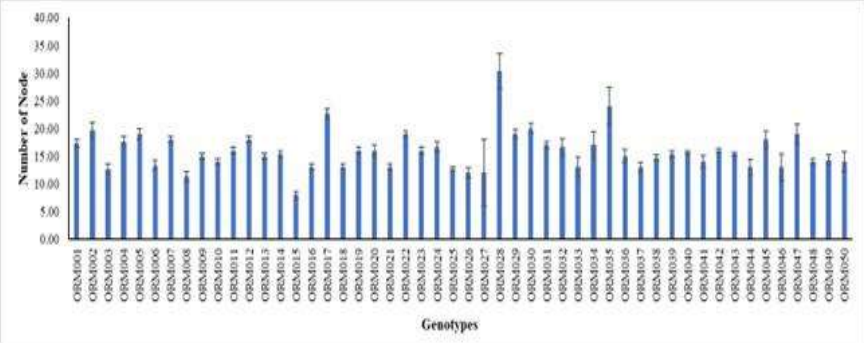

Figure 5: Phenotypic variation in number of nodes among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05).

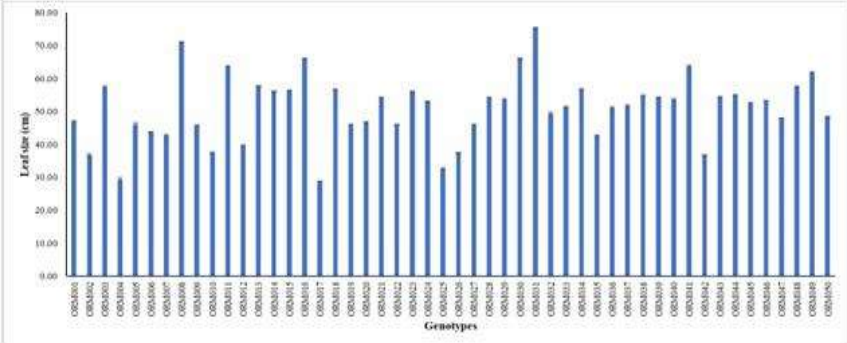

Figure 6: Phenotypic variation in leaf size among *Origanum majorana* clones evaluated under field conditions. Values represent mean leaf size (cm) ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05).

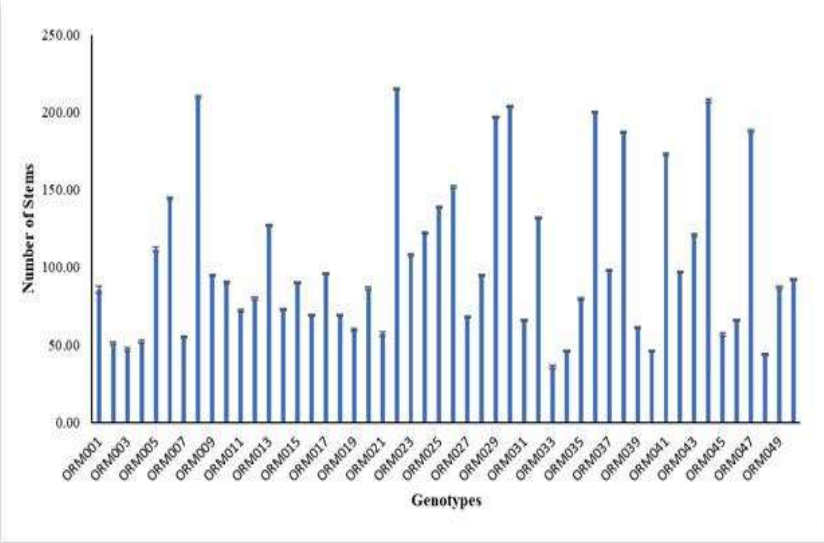

Figure 7: Phenotypic variation in number of tilleres among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05).

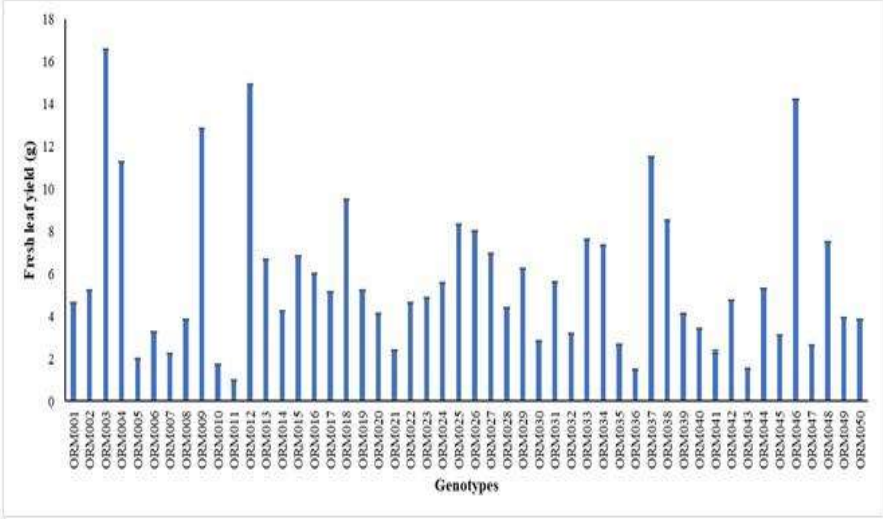

Figure 8: Phenotypic variation in fresh leaf yield among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05).

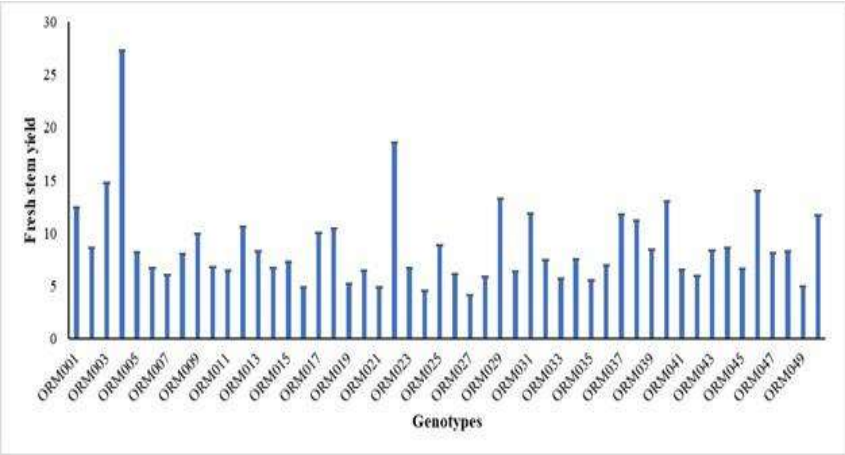

Figure 9: Phenotypic variation in fresh stem yield among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. Fresh stem yield observed from *Origanum majorana* clones. The mean values for clones varied significantly according to ANOVA (P≤0.05).

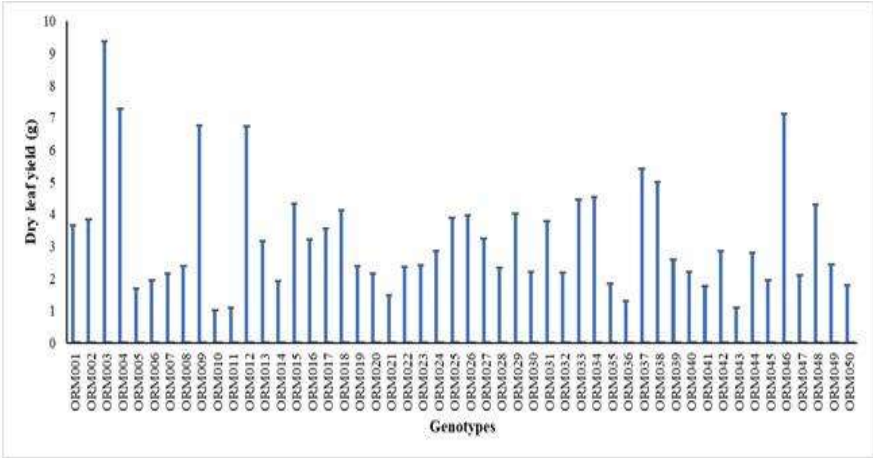

Figure 10: Phenotypic variation in dry leaf yield among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05).

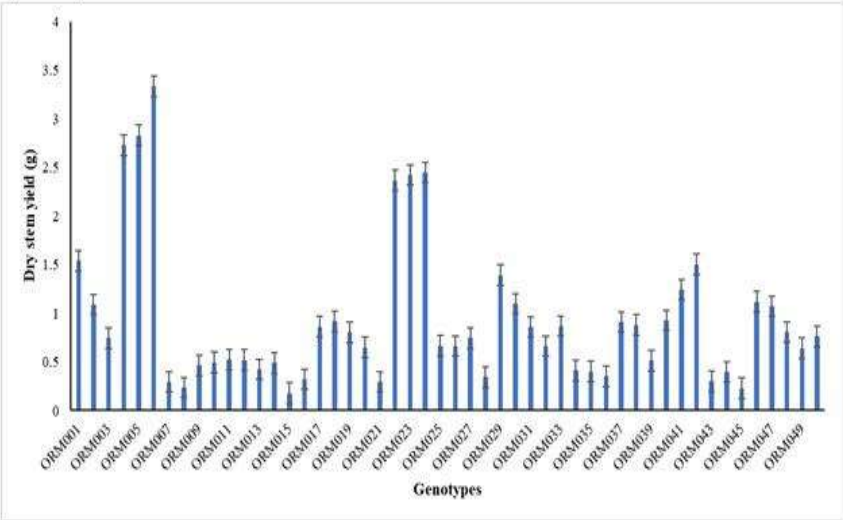

Figure 11: Dry stem yield variation among *Origanum majorana* clones. Data represent mean dry stem yield (g) ± standard error. The mean values for clones varied significantly according to ANOVA (P≤0.05).

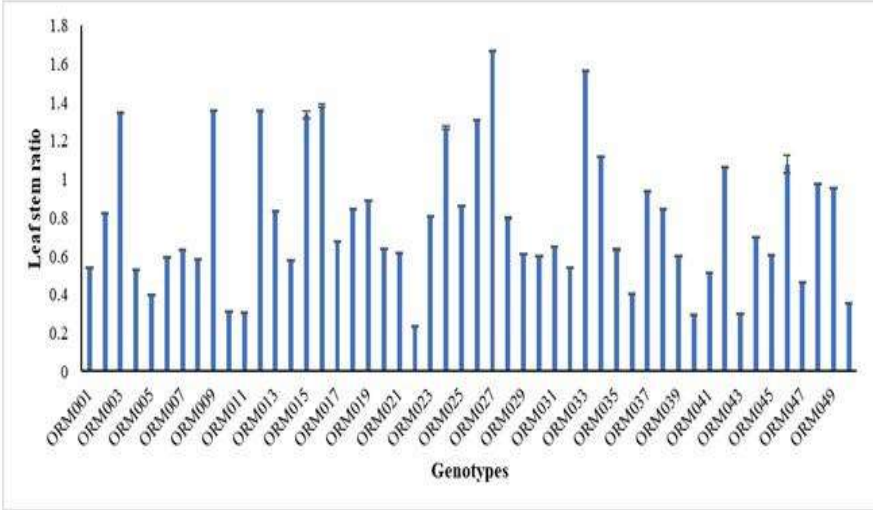

Figure 12: Phenotypic variation in leaf stem ratio among *Origanum majorana* clones evaluated under field conditions. Values represent mean ± SE. The mean values for clones varied significantly according to ANOVA (P≤0.05).

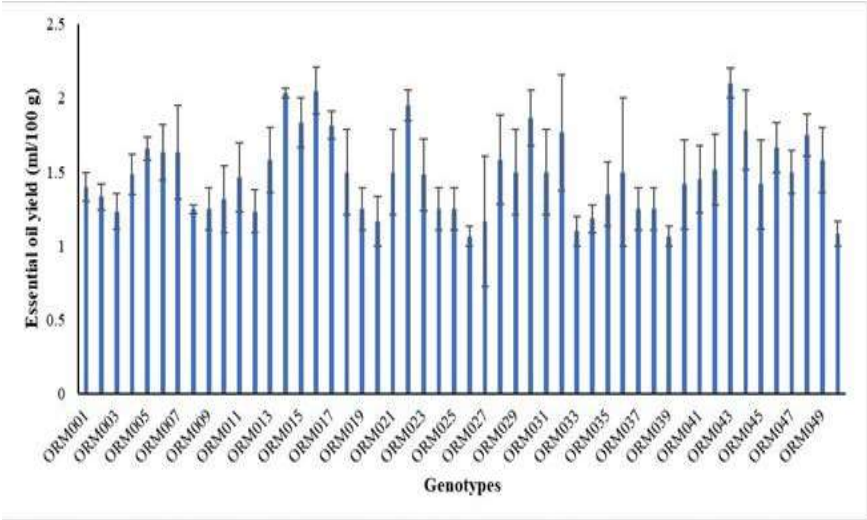

Figure 13: Genotypic variation in essential oil yield across 50 *Origanum majorana* clones. The bar graph shows mean essential oil yield (ml/100 g fresh weight) with standard error bars for each clones. The mean values for clones varied significantly according to ANOVA (P≤0.05).

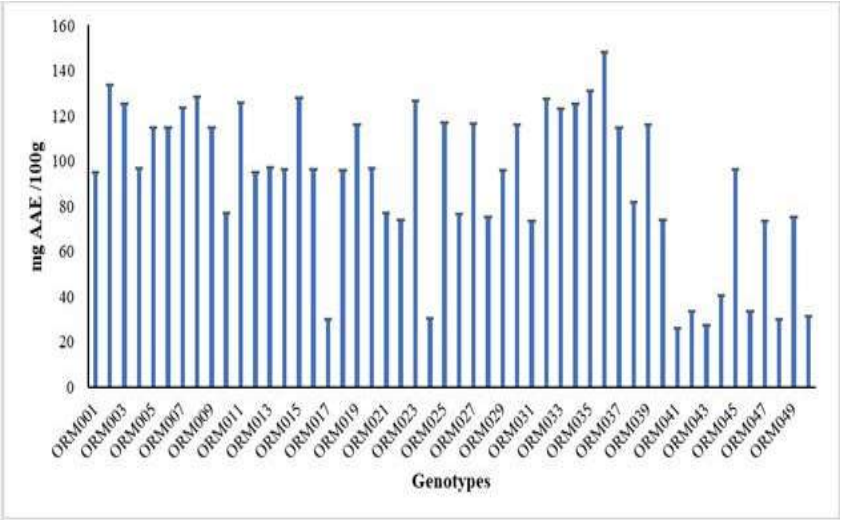

Figure 14: Antioxidant activity (mg AAE/100g) of *Origanum majorana* clones measured by DPPH radical scavenging assay. Data represents mean values ± standard error expressed as ascorbic acid equivalents. The mean values for clones varied significantly according to ANOVA (P≤0.05).

Table 2: Color parameters of fresh and dry leaves across 50 *Origanum majorana* L. clones. Color measurements were performed using CIE L*a*b* color space system, where L* represents lightness, a* represents green-red chromaticity, and b* represents blue-yellow chromaticity. Chroma indicates color saturation and Hue (H) represents color angle in degrees.

Clone	Fresh leaf color					Dry leaf color				
	L	a	b	Chroma	Hue (H)	L	a	b	Chroma	Hue (H)
ORM001	56.97	-3.44	21.14	21.42	350.8	40.43	2.48	11.06	11.33	12.64
ORM002	59.32	-4.14	19.26	19.70	347.9	43.91	2.96	12.97	13.30	12.86
ORM003	53.35	-3.24	17.82	18.11	349.7	48.14	2.12	13.75	13.91	8.75
ORM004	55.71	-3.88	19.86	20.24	348.9	43.11	2.45	12.24	12.48	11.32
ORM005	57.33	-2.55	22.75	22.89	353.6	48.07	1.61	9.67	9.80	9.45
ORM006	52.07	-3.29	15.05	15.41	347.7	44.32	3.91	13.64	14.19	16.00
ORM007	58.027	-4.15	25.06	25.40	350.6	46.69	2.63	12.99	13.25	11.43
ORM008	59.24	0.62	24.47	24.48	1.5	46.71	1.91	10.39	10.56	10.42
ORM009	62.15	-4.81	16.51	17.20	343.8	49.57	2.17	14.62	14.78	8.43
ORM010	58.67	-3.07	23.46	23.66	352.5	43.22	2.89	13.05	13.37	12.49
ORM011	58.52	-4.43	19.91	20.40	347.5	37.05	1.14	7.2	7.29	9.00
ORM012	56.52	-5.53	17.41	18.27	342.4	48.88	2.52	17.29	17.47	8.29
ORM013	53.02	-6.67	21.57	22.58	342.8	43.86	1.91	15.14	15.26	7.19
ORM014	50.13	-5.25	17.21	17.99	343.0	53.54	3.43	14.65	15.05	13.18
ORM015	46.85	-5.12	12.92	13.90	338.4	32.38	1.56	9.01	9.14	9.82
ORM016	61.14	-4.41	11.12	11.96	338.4	57.15	1.73	16.61	16.70	5.95
ORM017	54.14	-6.02	22.88	23.66	345.3	38.53	2.63	10.13	10.47	14.55
ORM018	57.76	-6.76	22.14	23.15	343.0	50.35	1.84	18.91	19.00	5.56
ORM019	56.12	-4.64	18.14	18.72	345.7	54.98	1.61	19.58	19.65	4.70
ORM020	57.41	0.56	13.92	13.93	2.3	42.76	3.31	13.39	13.79	13.89
ORM021	59.05	-4.71	22.71	23.19	348.3	48.53	1.76	13.26	13.38	7.56
ORM022	62.66	-5.75	25.85	26.48	347.5	38.05	2.59	11.05	11.35	13.19
ORM023	55.51	-4.21	17.48	17.98	346.5	46.57	2.91	13.2	13.52	12.43
ORM024	61.52	-4.79	26.56	26.99	349.8	49.08	2.48	17.88	18.05	7.90
ORM025	61.43	-5.55	23.98	24.61	347.0	49.44	4.12	13.23	13.86	17.28
ORM026	57.07	-6.45	23.84	24.70	344.9	48.26	1.92	18.2	18.30	6.03
ORM027	58.26	-4.58	22.12	22.59	348.3	47.45	1.12	17.68	17.72	3.64
ORM028	53.06	-1.53	18.96	19.02	355.4	41.35	3.2	12.93	13.32	13.90
ORM029	51.37	-2.94	17.98	18.22	350.7	39.75	3	11.35	11.74	14.81
ORM030	55.16	-4.23	21.62	22.03	348.9	35.65	1.73	10.09	10.24	9.73
ORM031	57.11	-4.22	20.02	20.46	348.1	48.17	2.08	15.87	16.01	7.47
ORM032	52.39	-3.66	17.45	17.83	348.2	43.18	2.39	11.16	11.41	12.09
ORM033	53.31	-4.58	15.55	16.21	343.6	44.24	2.29	13.57	13.76	9.58
ORM034	58.03	-1.32	22.87	22.91	356.7	35.51	1.93	9.11	9.31	11.96
ORM035	63.46	-4.55	27.88	28.25	350.7	46.34	4.51	13.73	14.45	18.18
ORM036	57.93	0.25	18.37	18.37	0.8	43.98	2.52	11.95	12.22	11.90
ORM037	53.31	-5.95	19.05	19.96	342.7	47.76	1.52	15.5	15.57	5.60
ORM038	59.74	-4.52	23.97	24.39	349.3	50.54	3.97	20.6	20.98	10.91
ORM039	57.80	-6.02	27.64	28.29	347.7	38.07	1.44	8.5	8.62	9.62
ORM040	67.22	-2.31	24.62	24.73	354.6	43.41	3.13	14.24	14.58	12.40
ORM041	59.08	-2.78	21.48	21.66	352.6	34.21	1.39	8.22	8.34	9.60
ORM042	53.63	-2.82	21.08	21.27	352.4	43.18	3.63	14.82	15.26	13.76
ORM043	61.58	-5.53	26.55	27.12	348.2	42.16	3.95	13.07	13.65	16.82
ORM044	59.787	-3.77	21.82	22.14	350.2	51.52	1.76	17.67	17.76	5.69
ORM045	50.01	0.32	15.14	15.14	1.2	46.17	2.81	12.72	13.03	12.46
ORM046	57.98	-1.45	22.72	22.77	356.3	37.92	2.8	12.61	12.92	12.52
ORM047	54.57	0.073	21.41	21.41	0.2	41.75	3.31	12.63	13.06	14.69
ORM048	60.32	-6.04	26.35	27.03	347.1	52.48	3.14	15.95	16.26	11.14
ORM049	61.37	-5.78	17.13	18.08	341.4	52.43	2.77	17.18	17.40	9.16
ORM050	59.86	-5.45	23.08	23.71	346.7	47.08	1.68	9.743	9.89	9.78

Principal component analysis was used to differentiate clones on the basis of morphology and biochemical traits (Figure 15). PCA among clones and traits studied showed a huge variation. Number of tillers, dry herbage yield, antioxidant activity and EOY were in the same group showing their strong dependence on each other and varieties such as ORM012, ORM013, ORM016, ORM018, ORM019, ORM027, ORM025, ORM033 and ORM034 were sharing these characters.

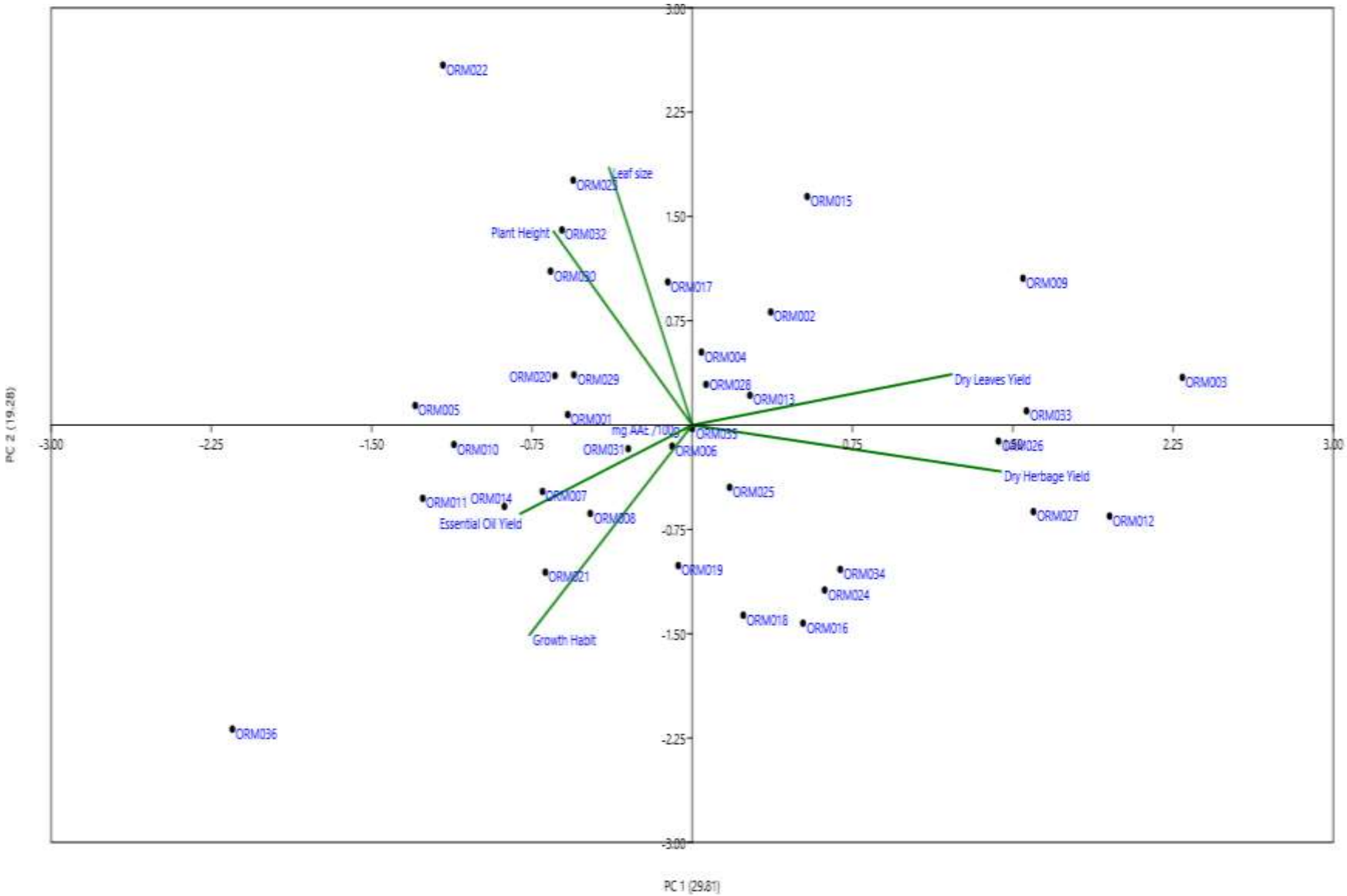

Figure 15: Principal component analysis (PCA) biplot of *Origanum majorana* clones based on morphological and biochemical traits. PC1 and PC2 explained 29.81% and 19.23% of the total variance, respectively.

Table 3: Correlation matrix showing relationships between agronomic traits measured in 50 *Origanum majorana* L. clones. Values represent Pearson correlation coefficients with significance levels indicated by asterisks (*$P < 0.05$).

	Clones	GH	NOS	IL	NON	LBL	LS	FHY	DHY	FLY	DLY	PH	AA	EOY
Clones	1													
GH	-.964**	1												
NOS	-.083	.081	1											
IL	-.069	.101	.015	1										
NON	-.023	.013	-.158	.068	1									
LBL	-.016	.029	-.014	.093	-.332*	1								
LS	.252	-.215	-.248	.236	.013	.293*	1							
FHY	-.044	-.036	-.084	-.189	-.311*	.199	-.293*	1						
DHY	-.065	.005	-.121	-.218	-.315*	.155	-.296*	.964**	1					
FLY	-.150	.150	-.012	-.119	-.244	.414**	-.082	.693**	.652**	1				
DLY	-.202	.235	-.006	-.099	-.189	.361*	-.042	.584**	.597**	.961**	1			
PH	-.049	.080	.016	.188	.164	.104	.153	-.344*	-.290*	-.129	-.052	1		
AA	-.468**	.432**	-.043	-.135	-.017	-.216	-.144	.080	.122	.039	.073	.006	1	
EOY	.097	-.100	.129	-.250	.020	-.067	.016	-.299*	-.250	-.262	-.243	-.049	.132	1

*= correlation significant ($P \leq 0.05$) and **= correlation significant ($P \leq 0.01$).

Note: GH: Growth Habit, NOS: No of Nodes, IL: Internode length, LBL: Longest Branch Length, LS: Leaf size, FHY: Fresh Herbage Yield, DHY: Dry Herbage Yield, FLY: Fresh Leaves yield DLY: Dry Leaves Yield, PH: Plant Height, AA: Antioxidant activity, EOY: Essential Oil Yield

A few clones were able to produce more than 2 g of dry stem weight.

The leaf stem ratio was significantly different among our targeted clones of *Origanum majorana* L. Clone ORM027 produced a significantly high leaf stem ratio of 1.6%. Clone ORM022 produced the lowest leaf stem ratio of only 0.2% (Figure 12). The average leaf stem ratio from each clone ranged from 0.4-0.8% while some clones were able to produce 1.4% of leaf stem ratio.

Essential oil yield of each *Origanum majorana* L. clone differed significantly among all targeted clones in the whole study. Clone ORM016 produced the highest essential oil yield of 2.0 mL 100 g^{-1} and these values were at par with the clone ORM042 (Figure 13). The clone ORM026 had the lowest EOY of less than 1.3 mL 100 g^{-1} followed by clones ORM003 and ORM032 (Figure 13). The average EOY was 1-2 mL 100 g^{-1} from each clone.

The antioxidant activity significantly differed among the clones of *Origanum majorana* L. Clone ORM035 produced significantly high antioxidant activity of 140 mg AAE/100 g while clone ORM041 produced the lowest antioxidant activity of only 20 mg AAE/100 g (Figure 14). The average antioxidant activity from each clone ranged from 80-120 mg AAE/100 g while only a few clones were able to produce more than 120 mg AAE/100 g of antioxidant activity.

The fresh and dry leaf color of *Origanum majorana* L. clones was significantly different (Table 2). The L value in fresh leaf color was highest (67.22) for ORM040 clones showed that the leaves of this clone had the brightest fresh leaf color. Clone RM015 showed the lowest L value (46.85) proving the darkest leaf color. The a^* The value was mostly negative which showed that fresh leaves were green for most of the clones while clones ORM008 and ORM020 showed a positive value, and the leaves were slightly reddish. The b^* values were mostly high among all clones with strong yellow pigmentation, and it was maximum for clones ORM035 and ORM039. Chroma for clones ORM035 and ORM038 was calculated higher than other clones and it showed the vivid leaf color of these clones.

The L values were lowest for maximum clones proving the darkest leaf color upon drying (Table 2). The chroma and hue values often shift, which reflects changes in pigment composition due when they dried. Some clones maintain higher chroma even after drying, like ORM018, ORM026, ORM035.

Data for correlation analysis showed that growth habit of *Origanum majorana* L. clones showed highly significant positive correlation with antioxidant activity and also correlation values were positive between growth habit and number of tillers, internode length, longest branch length, plant height, fresh leaf yield and dry leaf yield (Table 3). The correlation values were negative for leaf size and EOY. Antioxidant activity showed positive correlation with fresh herbage yield, dry herbage yield, fresh leaf yield and plant height. The EOY showed positive correlation with leaf size and antioxidant activity.

Essential oil extracted from dried aerial parts like leaf, flower and stem which are a highly complex mixture of compounds. Major constituents of essential oil were terpenoids and certainly monoterpenes sesquiterpene oxygenated sesquiterpene. Other compounds which have different functional groups like ester monoterpene acetates (Kakouri *et al.,* 2022). Sesquiterpene analysis showed a huge variation among the clones in terms of compounds present (Table 4). The 15 clones among 50 selected clones were used for GC-MS analysis on the basis of their agronomic features and biochemical traits. Overall, more than 70 compounds were observed from the clones. The high number of compounds were evaluated from ORM006 and ORM044 with 50 different compounds as mentioned in Table 4. The lowest number of compounds were recorded from ORM014.

Table 4: GC-MS-identified volatile compounds from essential oils of 15 *Origanum majorana* L. clones. The presence (✔) or absence (✘) of individual compounds is shown across clones. Detected compounds include monoterpenes, sesquiterpenes, phenolic constituents, and esters.

Compound Names	Clones														
	ORM 006	ORM 011	ORM 014	ORM 016	ORM 017	ORM 021	ORM 022	ORM 025	ORM 028	ORM 030	ORM 032	ORM 033	ORM 037	ORM 044	ORM 049
Heptane	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Cyclohexane, methyl-	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Butanoic acid, 2-methyl-, methyl ester	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	
Thujene	✔	✔	✔	✔	✔	✔	✔		✔	✔	✔	✔	✔	✔	✔
ALPHA.-PINENE	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Bicyclo[3.1.0]hex-2-ene, 4-methylene-1-(1-methylethyl)	✔	✔	✔	✘	✘	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘
Bicyclo[2.2.1]heptane, 2,2-dimethyl-3-methylene-	✔	✔	✘	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✔	✘
Vinyl amyl carbinol	✔	✔	✘	✔	✘	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘
Pinene	✔	✔		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘
Myrcene	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Hexanol	✔	✔	✘	✘	✔	✔	✔	✘	✔	✔	✔	✔	✔	✔	✘
1-Phellandrene	✔	✔	✘	✘	✘	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘
Delta 3-Carene	✔	✔	✘	✘	✘	✔	✔	✔	✔	✔	✘	✔	✔	✔	✘
alpha.-Terpinene	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘
o-Cymene	✔	✔	✔	✔	✘	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
D-Limonene	✔	✘	✘	✘	✘	✔	✔	✔		✔	✔	✔	✔	✔	✘
Sabinene	✔	✔	✘	✘	✔	✘	✘	✘	✘	✘	✘	✔	✘	✔	✔
EUCALYPTOL (1,8-CINEOLE)	✔	✔	✘	✔	✘	✘	✔	✔	✔	✔	✔	✔	✔	✔	✘
Ocimene	✔	✘	✘	✘	✔	✘	✘	✘	✔	✘	✘	✔	✘	✘	✘
gamma.-Terpinene	✔	✔	✔	✔	✔	✘	✔	✔	✘	✔	✔	✔	✔	✔	✔
trans Sabinene hydrate	✔	✔	✔	✔	✘	✘	✔	✔	✘	✔	✔	✔	✔	✔	✔
Alpha.-Terpinolene	✔	✔	✘	✘	✘	✘	✔	✘	✘	✘	✘		✔	✔	✘
Benzene, Methyl(1-Methylethenyl)-	✔	✔	✘	✘	✘	✘	✔	✘	✘	✔	✘	✔	✔	✘	✘
Linalool	✔	✔	✘	✘	✔	✘	✔	✘	✘	✔	✔		✔	✘	✘
Menth-2-en-1-ol	✔	✔	✘	✘	✘	✔	✘	✘	✔	✔	✘	✔	✔	✔	✘
endo-Borneol	✔	✔	✔	✔	✔		✔		✔	✔	✔	✔		✔	✔
3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-, (R)-	✔	✔	✔	✔	✔	✘	✔	✘	✘	✔	✔	✘	✘	✔	✔

PARA-CYMEN-8-OL	✔	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✔	✘
ALPHA. TERPINEOL	✔	✔	✘	✘	✔	✘	✘	✘	✘	✔	✔	✔	✔	✔	✘
CIS-DIHYDROCARVONE	✔	✘	✘	✘	✘	✘	✘	✘	✘	✔		✔		✔	
Benzene, 1-methoxy-4-methyl-2-(1-methylethyl)-	✔	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔	✔	✔	✘	✘
Linalyl acetate	✔	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘
Carvone	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘
D-Carvone	✔	✔	✘	✘	✘	✘	✔	✘	✘	✔	✘	✔	✘	✔	✘
Thymoquinone	✔	✘	✘	✘	✘	✘	✘	✘	✔	✔	✘	✔	✘	✔	✘
Phenol, 5-methyl-2-(1-methylethyl)-	✔	✘	✘	✘	✔	✔	✘	✘	✘	✘	✘	✔	✔	✘	✔
Phenol, 2-methyl-5-(1-methylethyl)-	✔	✘	✔	✘	✔	✔	✘	✘	✘	✘	✘	✔	✘	✔	✔
2-Ethyl-5-n-propylphenol	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✔	✘
Phenol, 2-methyl-5-(1-methylethyl)-, acetate	✔	✘	✘	✘	✘	✘	✔	✘	✘	✔	✘	✘	✘	✘	✘
BETA. BOURBONENE 563214 0.11	✔	✘	✘	✘	✔	✘	✘	✘	✔	✔	✘	✘	✘	✔	✘
Caryophyllene	✔	✘	✔	✔	✘		✔	✔	✔	✔	✔	✔	✔	✘	✔
1,4,7,-Cycloundecatriene, 1,5,9,9-tetramethyl-	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
GERMACRENE-D	✔	✘	✘	✘	✔	✘	✘	✘	✔	✔	✘	✘	✔	✔	✘
beta.-Bisabolene	✔	✘	✘	✘	✘	✘	✘	✘		✔		✘	✘	✘	✘
1H-Cycloprop[e]azulen-7-ol, decahydro-1,1,7-trimethy	✔	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔	✘	✔	✔	✘
Caryophyllene oxide	✔	✘	✘	✔	✔	✔	✘	✔	✘	✔	✔	✘	✘	✘	✘
1,1,3,3-Tetramethyl-1,3-bis{[5-methyl-2-(1-methylethenyl)hex-4-en-	✔	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
EICOSAMETHYLCYCLODECASILOXANE	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔
Cyclooctasiloxane, hexadecamethyl-	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔
Cyclononasiloxane, octadecamethyl-	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔
Cycloheptasiloxane, Tetradecamethyl-	✘	✘	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
Trans-beta-Ocimene	✘	✘	✘	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
Acetic acid	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘	✘	✔	✘	✘	✔
Cis-Ocimene	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘
L-linalool	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘	✘	✘	✘	✘
Beta-Phellandrene	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✔	✘	✘	✘
Thymol	✘	✘	✘	✘	✘	✘	✘	✘	✔	✔	✔	✘	✔	✘	✘
Elemol	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘	✘
Hotrienol	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✔	✔	✘
Geraniol	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘
Endobornylacetate	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✔	✘
Carvacrol	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘
1H-Naptho[2,1-b]pyran	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘	✘
Camphene (CAS)	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘
Bicyclogermacrene	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘	✘
Bergamal	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘	✘

Aromadrene	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✔	✘
Isospathulenol	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘	✘
Nerol	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔	✘
Cia-Farnesol	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✔

Table 5: Range of major essential oil constituents identified in 15 clones of *Origanum majorana* L. based on GC-MS analysis. The observed variation in compound percentages reflects underlying clone diversity.

Compound Name	%Range Observed
Linalool	17.5 – 76.5%
Phenol, 2-methyl-5-(1-methylethyl)- (*Carvacrol*)	4.76 – 67.69%
1,6-Octadien-3-ol, 3,7-dimethyl- (*Likely Geraniol/Nerol/Linalool isomers*)	12.44 – 83.73%
o-Cymene	0.84 – 21.43%
γ-Terpinene	0.14 – 5.92%
Thymol	0.32 – 6.81%
Caryophyllene	0.16 – 1.14%
Endo-Borneol	0.29 – 2.38%
α-Terpinene	0.13 – 1.30%
Sabinene Hydrate (cis- and trans-)	0.20 – 1.93%

DISCUSSION

Origanum majorana L. keeps a significance in Lamiaceae family because of its high antioxidant activity, EOY, antibacterial and antiviral qualities (Kakouri *et al*., 2022). Agronomic traits play a significant role in growth and development of *Origanum majorana* L. like plant length, number of nodes, internode length, number of branches, and leaf size etc. *Origanum majorana* L. showed a complex mixture of monoterpene hydrocarbon, oxygenated monoterpene phenolics compound, sesquiterpene oxygenated sesquiterpenes esters, alcohol, and ketone. Apart from these there are some minor aromatic volatile organic compounds. A table above shows a list of compounds which are majorly present in fifteen clones in essential oil (Table 5). EOY depends on morphology, time of harvesting, and aerial parts which are used in extraction of essential oil (Ragab *et al*., 2019; Prabu *et al*., 2020). Continuous climate changes cause stress and lead to a change in the pattern of yield and affect the component of EOY. In the current study, morphological and biochemical traits of fifty clones were evaluated.

The morphological parameters of *Origanum majorana* L. play a significant role in evaluating plants' growth performance, herbage yield, EOY and antioxidant activity. The recorded parameters in the study: growth habit, no. of nodes, internode length, longest branch length, leaf size, fresh herbage yield, dry herbage yield, fresh leaves yield, dry leaves yield, plant height, antioxidant activity, EOY and secondary metabolites by using GC-MS have a crucial role in determining plants' overall performance and adaptability in a specific area.

In the current study, clones exhibiting erect types of growth habits with high number of branches produced greater biomass as compared to bushy or semi-erect clones. The reason for the increase in biomass production is the improved light interception to the plants due to wide canopy structure under erect growth habit (Anonymous, 2010; Davidenco *et al.*, 2020). Moreover, the high leaf area index also caused an increase in biomass production (Azizi *et al.*, 2009). The plant height of clones in the current study varied between 60-80 cm which is in line with a previous study conducted by researchers. The number of nodes and length of internodes determine the performance of vegetative propagation and their capacity to elongate their shoots. Both these parameters are important for continuous vegetative growth on a sustainable basis. Also, the number of nodes and length of internodes play a vital role in sustaining flower initiation (Baser and Buchbauer, 2010). Plants traits such as leaf size have a direct role in photosynthesis process and it also has a crucial role in biosynthesis of essential oil due to the source of primary sites for oil gland accumulation in the *Origanum majorana* L. plants. Large leaf areas along with optimal glandular trichome density play a major role in synthesis of higher EOY and specific oil composition in the *Origanum majorana* L. and other medicinal plant species (Bozin *et al.*, 2006; Shafiee-Hajiabad *et al.*, 2015). The fresh and dry herbage and leaf yields are key economic traits in *Origanum majorana* L. and were positively associated with one another, indicating that selection for high biomass may simultaneously improve EOY. However, EOY showed weak or negative associations with some morphological parameters such as plant height or internode length, suggesting that oil production is more closely linked to leaf morphological traits and glandular structures than overall plant size and is proved with the previous studies (Kokkini and Vokou, 1989;

Santos-Gomes and Fernandes-Ferreira, 2001; Adeniran *et al*., 2025). The secondary metabolites constituents proved an inverse correlation with antioxidant activity (Table 4). The clone ORM014 produced high antioxidant activity while a smaller number of secondary metabolites constituents.

The leaf color values of both the fresh leaf color and dry leaf color showed a significant difference among the clones in the current study (Table 2). The L values were the lowest for maximum clones proving the darkest leaf color upon drying. The chroma and hue values often shift, which reflects changes in pigment composition due to drying (e.g., chlorophyll degradation and exposure of carotenoids or phenolics). Some clones maintain higher chroma even after drying, like ORM018, ORM026, ORM035, suggesting potential for consistent color quality in dried herb products.

Principal component analysis (PCA) is recognized as a valuable statistical tool for analyzing multivariate data sets characterized by high correlations among variables (Johnson, 1998). The EOY showed positive correlation with leaf size and antioxidant activity (Table 3). The more antioxidants the more EOY. This has been proved by a previous study that showed a significant positive correlation between leaf size and fresh/dry leaf yield, which, in turn, are strong indicators of oil content and overall quality of the secondary metabolites (Said-Al Ahl and Omer, 2009).

GC-MS analysis of essential oil of selected 15 clones of *Origanum majorana* L. exposed significant chemical variability among clones. Linalool was the compound found in most of the clones. Percentage of linalool was 17.5 to 76.5% followed by carvacrol (2-methyl-5-(1-methylethyl)-phenol) ranging from 4.7 % to 67.69% and 1,6- Octadien-3-ol, 3,7-dimethyl- up to 83.7 % in some clone showed chemotypes dominance. γ-terpinene, o-cymene, thymol, and borneol compounds contribute to antimicrobial properties, antioxidant and therapeutic values. This heterogeneity among clones reveals the potential for breeding and selection programs that is focused on enhancement of certain essential oil profiles, specially which is rich in linalool or phenolic constituents like carvacrol and thymol these phenolic compounds recognized as bioactive compound against pathogen, like *Escherichia coli*, *Salmonella spp.*, and *Candida albicans* (Sharifi-Rad *et al.,* 2017; Da Silva *et al.*, 2020, Baranauskaite *et al*., 2017).

Overall, the current study underlines the importance of key morphological parameters such as leaf size, branching habit, and biomass traits in improving yield and possibly enhancing secondary metabolite content in the selected *Origanum majorana* L. clones. These traits should be prioritized in selection programs aiming for dual improvement of yield and phytochemical quality in *Origanum majorana* L. plants.

Conclusion: In the present study, important agro-morphological traits like leaf size, growth habit, and cumulative biomass were found to be significantly influenced by the content of essential oil, herbage yield and patterns of secondary metabolites in the evaluated clones. Among them, clone ORM025 revealed superior vegetative growth and highest essential oil production, indicating its potential for industrial cultivation. clone ORM014 exhibited maximum antioxidant activity, indicating its potential for nutraceutical exploitation. In addition, ORM006 and ORM044 had remarkable phytochemical richness, with the highest number of volatile compounds to be identified and implying high biosynthetic potential.

These findings highlight tremendous variability in *Origanum majorana* L. clones that can be managed strategically for selection and breeding to produce valuable high-yielding cultivars with a known chemical composition. The integration of morphological traits with phytochemical profiling in the current research offers an efficient approach for the selection of elite germplasm having enhanced industrial utility. Future breeding programs should focus on such valuable clones to optimize essential oil production as well as bioactive compound content to ensure sustainable agriculture and medicine application.

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