

Research

Potential of *Tagetes minuta* L. populations as a high-yield crop for essential oil production in Garhwal Himalaya, India

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Abstract

Although a weed in many parts of the world, *Tagetes minuta* L. has become a crop of commercial importance. The current study assessed the morphological variation and oil yield of *T. minuta* from various populations in the Garhwal, Himalayan region, aiming to identify those with high yields. Results revealed that the qualitative morphological features of *T. minuta* populations were consistent across all samples, suggesting a uniform genetic makeup. However significant ($p \leq 0.05$) variation was detected in quantitative morphological traits among the populations. With Barsu exhibiting the tallest plants and Gangnani showing the greatest leaf length and number of leaflets per leaf. The Barsu population also demonstrated superior biomass and essential oil yields at both pre- and full-flowering stage. At the full-flowering stage, fresh biomass, essential oil content, and yield were 7.48%, 52.04%, and 55.16% higher, respectively, compared to the pre-flowering stage. However, stem biomass at the full-flowering stage decreased by 8.25% relative to the pre-flowering stage. Strong positive correlations were revealed between plant height, biomass, and oil yield, with taller plants showing higher productivity. Geographical variables, such as latitude and longitude, influenced various morphological and yield traits, particularly highlighting increased values towards higher latitudes and more eastern regions. Additionally, phenotypic and genotypic analyses underscored high variation in traits such as the number of main branches and biomass yield, with heritability estimates suggesting potential for targeted breeding. The highest genetic gain was observed for the number of primary branches and stem biomass, indicating opportunities for future improvements in essential oil production. This study highlights the potential of *T. minuta* for essential oil production and emphasizing the importance of both genetic and environmental factors in yield variation.

Keywords Flowering stage · Hydro-distillation · Oil yield · Populations · *Tagetes minuta* · Variability

1 Introduction

Tagetes minuta, commonly known as wild marigold, is an annual herb native to South America [1] and recognized as an invasive weed in various regions worldwide. In India, it has naturalized in the Himalayan and sub-Himalayan regions, thriving at altitudes ranging from 1000 to 2500 m [2, 3]. This plant, characterized by its erect, woody structure

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and highly aromatic foliage, typically grows to a height of 0.5–2 m. It is frequently found in wastelands, along roadsides, on rocky hill slopes, and in cultivated fields [4]. Indigenous population use *T. minuta* as a spice and medicinal herb [5]. The essential oil extracted from the aerial parts of *T. minuta*, including leaves, flowers, and seeds, is highly valued for its distinct aroma and beneficial properties [6]. The major components of essential oil are (Z)- β -ocimene, dihydrotagetonone, (Z)-tagetone, (E)-tagetone, (Z)-tagetenone, (E)-tagetenone, (Z)-ocimenone and (E)-ocimenone [7]. The essential oil, in high demand, is extensively utilized in the flavour and perfumery industries [5–8], particularly in high-grade perfumes and as a flavouring agent in products like ice creams, candies, liquors, puddings, and gelatins [6–9]. The oil's bioactive and therapeutic properties [10, 11], including its allelopathic potential against obstructive weeds and anti-cancerous activity, are well-documented [12–14]. With the essential oil market projected to grow to USD 11.8 million by 2025 at a CAGR of 7.0%, *T. minuta* holds significant economic potential [15] (Fig. 1).

The Garhwal Himalaya is an integral part of the Himalayan mountain system and lies in the northern part of India. The Garhwal Himalaya covers an area of about 29,089 km² and comprises of four agro-climatic zones—tropical (0–500 m), sub-tropical (500–1000 m), temperate (1000–2000 m), and cold (above 2000 m) [16]. The traditional farming is becoming difficult in Himalayan region due to the degradation of crops by wild animals specially monkeys, wild boar etc. and is causing huge economic losses to farmers [17–19]. Wild marigold is minimally affected by vermins, shows remarkable resistance to noticeable diseases, and holds significant potential for enhancing livelihoods in rural areas. In the temperate climate, it produces the best growth and quality oil due to a fall in the night temperature which is favourable for the plant [20].

Given the commercial importance of *T. minuta*, the essential oil yield, dependent on both oil content and biomass yield, is crucial. Morphological and growth attributes directly influence biomass production, serving as comparative measures for evaluating the species. The presence of variations among plant populations is essential for selecting superior germplasm, further propagation, and commercial cultivation. However, research on the wild populations of *T. minuta* in the Garhwal Himalayan region remains scarce. Limited research has been conducted on the distribution, population dynamics, genetic variation, and chemical properties of *T. minuta* across the Garhwal Himalayas. Studies exploring the relative influence of genetic and environmental factors on yield variability in Himalayan populations are also scarce. Additionally, there is limited research on the essential oil yield and its economic significance. In this article, we aim to evaluate variations in morphological parameters, yield attributes, and essential oil production from selected populations to address the following research questions: (i) do different isolated populations cause morphological variation in *T. minuta*? (ii) is there variation in essential oil yield based on plant age and climatic conditions of the populations?

2 Materials and methods

2.1 Study area

This study was conducted at the experimental field of the College of Forestry, Ranichauri, Uttarakhand. Fourteen distinct populations of *Tagetes minuta* were identified across the Garhwal Himalaya (Fig. 2, Table 1). In November 2018, phyllaries were collected from randomly selected healthy plants exhibiting vigorous growth, fruiting, and being free from diseases within the selected populations. The phyllaries were shade-dried for seven days, and the seeds were subsequently extracted. These cleaned seeds were then stored in paper bags for further study.

2.2 Experimental design and cultivation

Seeds were sown in the first week of April 2019 in a polyhouse and were transplanted 45 days after sowing (DAS). The soil in the experimental fields was silt loam with a pH of 6.5, containing available nitrogen (194.43 kg ha⁻¹), phosphorus (19.65 kg ha⁻¹), and potassium (44.8 kg ha⁻¹). The climate of experimental site is humid and temperate type with mild summer and chilling winter. The average maximum and minimum temperature ranged from 22.87 °C to 12.01 °C respectively during the crop period. The maximum rainfall (175.6 mm) was recorded in July while minimum (21.3 mm) in May (Supplementary Fig. 1). Forty-five-day-old seedlings were transplanted at a spacing of 30 × 30 cm in a randomized block design, with three replicates of 20 plants each per population. Transplanting was followed by light irrigations and the addition of farmyard manure (FYM) to support seedling establishment. The experimental field was kept weed-free through periodic weeding. Irrigation was provided at intervals of 2 to 5 days, adjusted according to the soil moisture

Fig. 1 *Tagetes minuta*; plants (A), leaves (B) and flowers (C)



status and crop requirements. Gap filling was conducted on the 30th day after transplanting to maintain uniform plant populations in all plots. Staking was provided to the plants at the time of flowering, where necessary.

2.3 Observations

2.3.1 Morphology and biomass

The plants were monitored throughout their life cycle, with observations made on plant habit, stem and leaf type, inflorescence type and floral structure, flowering initiation, and flowering duration. During the pre-flowering phase,

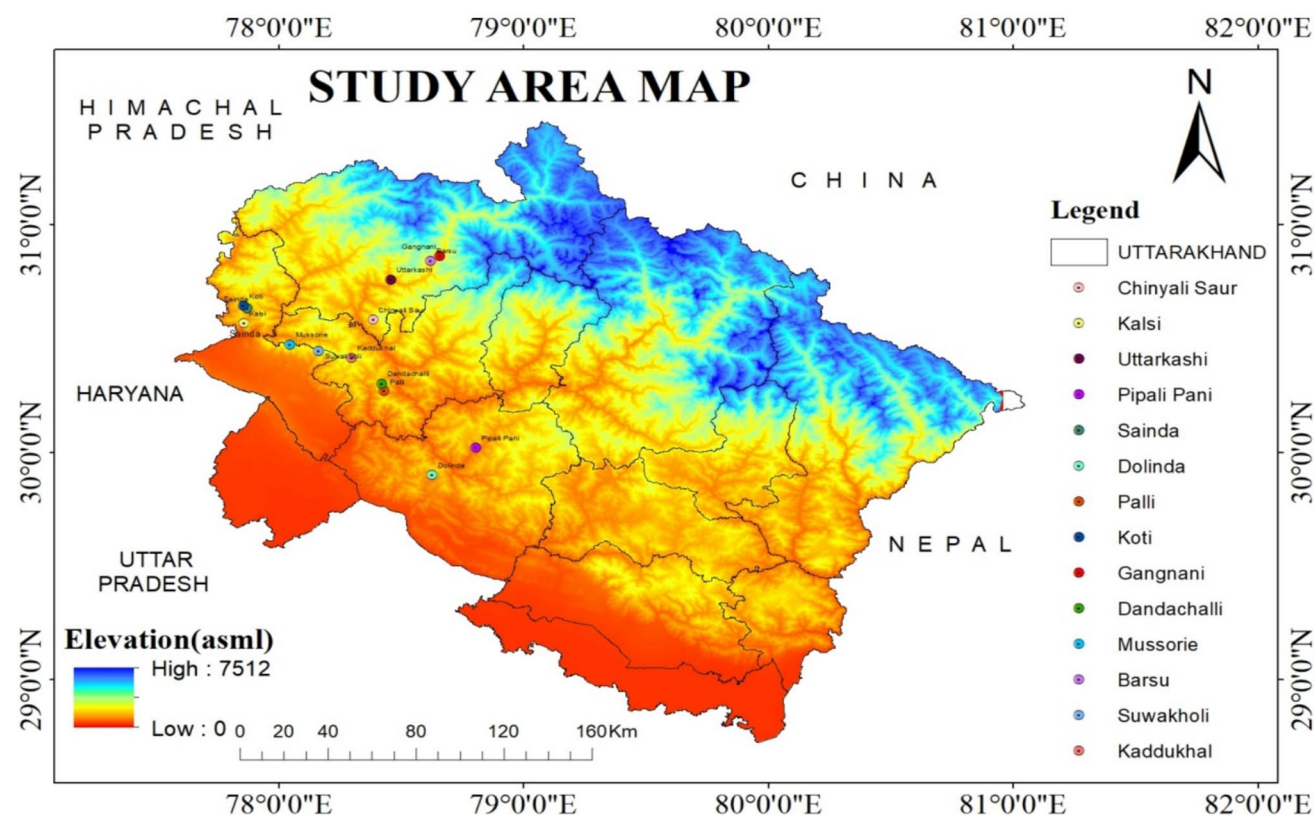


Fig. 2 Study areas map

Table 1 Geographic information of selected sites

Site	District	Elevation(m amsl)	Latitude (°N)	Longitude(°E)
Palli	Tehri	1333	30° 16' 10.56"	78° 25' 55.02"
Dandachalli	Tehri	1923	30° 18' 01.08"	78° 25' 22.08"
Suwakholi	Tehri	2086	30° 26' 38.76"	78° 09' 52.92"
Kaddukhal	Tehri	2374	30° 24' 00.54"	78° 17' 52.44"
Chinyali Saur	Uttarkashi	867	30° 34' 53.76"	78° 23' 12.48"
Uttarkashi	Uttarkashi	1165	30° 45' 31.32"	78° 27' 25.56"
Gangnani	Uttarkashi	1865	30° 51' 39.24"	78° 39' 28.08"
Barsu	Uttarkashi	2021	30° 50' 29.04"	78° 37' 18.12"
Kalsi	Dehradun	934	30° 33' 58.32"	77° 51' 30.06"
Sainda	Dehradun	1230	30° 37' 52.68"	77° 52' 23.88"
Koti	Dehradun	1428	30° 38' 36.24"	77° 51' 23.04"
Mussorie	Dehradun	1997	30° 28' 23.52"	78° 02' 52.08"
PipaliPani	Pauri	1175	30° 01' 10.92"	78° 48' 20.88"
Dolinda	Pauri	1256	29° 53' 58.92"	78° 37' 42.24"

leaf length and the number of leaflets per leaf were documented from leaves at the mid-level of the plant. Plant height, collar diameter, and the number of branches per plant were recorded at the full-flowering stage. Five randomly selected plants were used for measuring plant height, collar diameter, and biomass yield per replication. For leaf length, at least five leaves per plant from five plants per replication were measured. Fresh biomass yield was recorded at two stages: pre-flowering and full-flowering. At the pre-flowering stage, leaf and stem portions were separated and weighed separately. At the full-flowering stage, the entire mature floral region was separated from the stem portion and weighed separately. The biomass recorded per plant was later converted to biomass yield per hectare.

2.3.2 Essential oil yield

Essential oil extraction was performed at both the pre-flowering (leaf oil yield) and full-flowering (floral oil yield) stages. Leaves and flowering portions were immediately distilled after harvesting using a Clevenger-type apparatus. Hydro-distillation was carried out for 3–4 h until no further essential oil was recovered. A 250 g sample was taken per replication. The essential oil percentage (content) recorded was then converted to essential oil yield per hectare [21].

2.3.3 Data analysis

Variation analysis was conducted using WASP 2.0 software, and differences among populations were compared using the critical difference (CD) at a 5% level of probability. Correlation analysis was performed using OPSTAT software to determine the strength of the linear relationship among morphological and yield parameters, as well as the relationship of latitude, longitude, and altitude with these parameters.

Phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV), and heritability (h^2) in the broad sense were calculated using the formula provided by Burton and Devane [22]. Genetic advance and genetic gain were calculated according to the methods recommended by Allard [23] and Johnson et al. [24], respectively. For categorizing the magnitude of PCV, GCV, heritability, and genetic gain, the limits established by Pal et al. [25] were followed.

PCV and GCV	> 30%	–	High
	15–30%	–	Moderate
	< 15%	–	Low
Heritability (h^2)	> 80%	–	High
	50–80%	–	Moderate
	< 50%	–	Low
Genetic gain	> 50%	–	High
	25–50%	–	Moderate
	< 25%	–	Low

3 Results

3.1 Morphological characteristics

The plants across all populations exhibited uniform characteristics, with annual, erect stems that were ribbed, glabrous, and profusely branched at the base or above, becoming slightly woody at maturity. The initial growth phase was marked by a full flush of leaves from the nursery to the full vegetative stage. The leaves were pinnately compound with a prominent mid-rib, pungent, slightly glossy, dark green on the adaxial surface, and light green on the abaxial surface. Leaf arrangement (phyllotaxy) was mostly opposite in the lower plant portion and slightly alternate in the upper plant portion. The leaflets were linear, acute, and lanceolate with finely serrate margins. Small translucent orange-coloured glands were present on the undersurface of the leaves, more prominent, elliptical, and larger towards the margins compared to the oval-shaped glands near the mid-vein.

As the plant entered the reproductive stage, leaf senescence began, reducing the number of leaves in the lower plant portion and initiating secondary branching in the upper plant portion. At full flowering, the lower plant portion was entirely devoid of leaves, with leaves only present in the upper parts of the plant. By the seed-setting stage, almost all the leaves had dried.

The inflorescence consisted of phyllaries arranged in a cyme, composed of ray and disc florets. Three to five phyllaries emerged from a single growing point. Initially green, the phyllaries turned yellowish at maturity (seed-setting stage). Orange-colored glands on the phyllaries were linear in shape and more prominent than those on the lower surface of the leaves. Flowering initiation occurred in the first week of September, lasting up to October for approximately 5 to 6 weeks.

The maximum plant height was recorded in Barsu (225.87 cm), while the minimum was in Sainda (166.07 cm). Collar diameter ranged from 10.78 mm (Suwakholi) to 17.80 mm (Barsu). The highest number of primary branches per plant was observed in Uttarkashi (12.00) and the lowest in Koti (3.53). The Gangnani population exhibited the maximum leaf length (20.80 cm) and the highest number of leaflets per leaf (17.20), while the Dolinda population had the minimum values (15.41 cm and 12.27, respectively).

3.2 Biomass and essential oil yield

During the pre-flowering stage, the Barsu population exhibited the highest fresh leaf biomass at 70.55 q ha^{-1} , essential oil content at 0.30%, and essential oil yield from leaves at 21 L ha^{-1} . In contrast, the Uttarkashi population demonstrated the maximum stem biomass at 362.93 q ha^{-1} .

At the full-flowering stage, the Barsu population again showed superior performance, with the highest fresh flowering portion biomass at 74.18 q ha^{-1} , essential oil content at 0.60%, and essential oil yield from the flowering portion at 44.51 L ha^{-1} . The Uttarkashi population continued to exhibit the maximum stem biomass at 338.11 q ha^{-1} .

At both stages Barsu population excelled in terms of biomass and oil yield. This is particularly notable for commercial production, as high biomass and essential oil yield can translate to increased raw material availability and higher production efficiency, benefiting the profitability of essential oil extraction enhancing both product and monetary value. While Uttarkashi population reported higher stem biomass this may have less direct impact on essential oil production, as stems typically yield lower oil content compared to leaves and flowers.

3.3 Correlation analysis

Correlation studies revealed that leaf oil yield is most strongly and positively correlated with leaf biomass yield ($r = 0.931$). Leaf biomass yield exhibited a highly significant correlation with plant height ($r = 0.781$). Among the leaf parameters, leaf oil yield showed a non-significant correlation with the number of leaflets per leaf but had a significant positive correlation with leaf length ($r = 0.607$).

The oil yield from the flowering portion was also highly positively correlated with floral biomass ($r = 0.856$). Floral biomass demonstrated a strong direct correlation with plant height ($r = 0.895$). Additionally, oil yield from the flowering portion was significantly correlated with leaf parameters (Table 4).

Regarding geographical variables, altitude had a non-significant relationship with all morphological and yield parameters of *Tagetes minuta*. Latitude showed a significantly positive correlation with leaf length, the number of leaflets per leaf, essential oil content in the flowering portion, and essential oil yield at the full-flowering stage, indicating a northern trend. Longitude had a significant positive relationship with plant height, stem collar diameter, the number of main branches per plant, leaf biomass at the pre-flowering stage, stem biomass at the pre-flowering stage, essential oil yield at the pre-flowering stage, and flowering portion biomass yield at the full-flowering stage, suggesting that these parameters increase towards the eastern extremes (Table 5).

3.4 Phenotypic and genotypic variation

The phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) were highest for the number of main branches per plant (PCV = 42.25; GCV = 39.69) and lowest for leaf length (PCV = 8.93; GCV = 6.38).

Heritability (h^2) in the broad sense ranged from 11.77% to 98.65%. The highest heritability was recorded for stem biomass at the full-flowering stage (98.65%), followed by stem biomass at the pre-flowering stage (97.81%), while the lowest heritability was observed for leaf length (51.15%) and the number of leaflets per leaf (64.66%).

Genetic gain (GG) varied from 0.65 to 76.79. The highest genetic gain was observed for the number of primary branches per plant (76.79), followed by stem biomass at the full-flowering stage (58.12). The minimum genetic gain was recorded for leaf length (9.41), followed by the number of leaflets per leaf (12.53) (Table 6).

4 Discussion

Tagetes minuta, an important aromatic exotic species, has successfully naturalized across various regions of India, including Uttarakhand. Due to its valuable aromatic oil, which is highly sought after by perfumery and flavouring industries globally, modest commercial activity has begun in several parts of the country [8]. This study evaluated different populations of *T. minuta* collected from the Garhwal Himalaya under controlled environmental conditions, thereby minimizing environmental variability and attributing observed variations primarily to genetic factors specific to the study site. The absence of significant differences in qualitative morphological traits among populations suggests a uniform genetic makeup across these populations. This finding aligns with previous studies on *T. minuta* by Singh et al. [20], Sadia et al. [26], Gakuubi et al. [11], Lizarraga et al. [27], and Kumar et al. [28].

Variation in flowering initiation from July to November was observed in natural habitats, underscores the strong influence of environmental conditions on the timing and duration of flowering [29], consistent with findings by Hulina [30] and Ofori et al. [31]. The economic significance of *T. minuta* lies in its flowering biomass, which can be extended under favourable environmental conditions. Significant variations ($p \leq 0.05$) were noted in plant height, collar diameter, number of primary branches per plant, leaf length, and number of leaflets per leaf (Table 2), characteristics known to be governed by genetic factors and influenced by genotype-environment interactions across different populations. While literature reports plant heights up to 2 m [11, 20, 26, 30, 32], heights exceeding 2 m were observed in populations such as Chinyali Saur, Uttarkashi, PipaliPani, Palli, Gangnani, Dandachali, and Barsu (Table 2). These genotypes might be particularly well-adapted to certain environmental conditions in the region. Potential environmental factors influencing these differences may include variations in soil fertility, moisture levels, altitude, and temperature. The use of farmyard manure during transplanting, as noted, could provide essential nutrients that boost growth, enhancing plant height and overall biomass, as observed by Kumar et al. [33] and Walia and Kumar [34].

Increased primary branches could be a response to transplanting stress-induced pinching effects on seedling upper parts, a phenomenon noted by Rathore et al. [35] and Kumar et al. [36] in *T. minuta* and *T. erecta*, respectively. Leaf characteristics exhibited interdependence, where populations with longer leaves also displayed higher leaflet numbers per leaf, and vice versa (Table 2), consistent with findings by Ofori [31], Gakuubi et al. [11], and Lizarraga et al. [27].

Commercial success of economically important plant species hinges on their productivity and yield. Therefore, evaluating high-yielding germplasm is crucial for improving productivity and economic returns. In *T. minuta*, leaves and flowering parts are economically significant. Leaves of *T. minuta* develop profusely before flowering initiation and subsequently senesce with flower development, necessitating separate evaluation of germplasms for leaf and flowering biomass and

Table 2 Plant height, collar diameter, number of primary branches per plant, leaf length and number of leaflets per leaf in 14 populations of *Tagetes minuta*

Populations	Plant height (cm)	Collar diameter (mm)	No. of primary branches/plant	Leaf length (cm)	No. of leaflets/leaf
Chinyali Saur	215.87 ^{ab}	16.23 ^{abc}	8.00 ^c	19.57 ^{ab}	16.20 ^{abc}
Kalsi	195.07 ^{cde}	12.20 ^{def}	4.40 ^{ef}	18.15 ^{bcd}	15.33 ^c
Uttarkashi	217.87 ^a	16.13 ^{bc}	12.00 ^a	19.09 ^{abc}	16.33 ^{abc}
PipaliPani	205.07 ^{bc}	14.63 ^c	6.00 ^d	16.62 ^{de}	13.53 ^d
Sainda	166.07 ^f	12.40 ^{def}	4.07 ^{ef}	17.46 ^{cd}	15.13 ^c
Dolinda	184.00 ^e	12.57 ^{de}	10.67 ^{ab}	15.41 ^e	12.27 ^d
Palli	200.07 ^c	12.67 ^d	4.87 ^{def}	18.31 ^{bcd}	15.73 ^{bc}
Koti	186.47 ^{de}	11.53 ^{def}	3.53 ^f	17.91 ^{bcd}	15.80 ^{abc}
Gangnani	215.73 ^{ab}	16.57 ^{ab}	8.27 ^c	20.80 ^a	17.20 ^a
Dandachali	225.47 ^a	11.00 ^{ef}	5.53 ^{de}	18.26 ^{bcd}	16.33 ^{abc}
Mussorie	199.47 ^c	12.13 ^{def}	5.53 ^{de}	17.63 ^{cd}	15.47 ^{bc}
Barsu	225.87 ^a	17.80 ^a	9.47 ^{bc}	19.54 ^{ab}	16.80 ^{ab}
Suwakholi	183.80 ^e	10.78 ^f	4.13 ^{ef}	17.44 ^{cd}	15.40 ^{bc}
Kaddukhal	196.27 ^{cd}	11.63 ^{def}	5.47 ^{de}	18.25 ^{bcd}	15.80 ^{abc}
Mean	201.22	13.45	6.27	18.17	15.52
CD _{0.05}	11.909	1.623	1.598	1.903	1.457

Means followed by the same letter are not significantly ($p < 0.05$) different

oil yield. Significant variations ($p \leq 0.05$) were observed among populations for all yield parameters studied at both pre-flowering and full-flowering stages (Table 3). Crop yield potential results from the combined effects of growth, development, and qualitative performance under specific eco-climatic conditions, influenced by prevailing weather during the growth period and genetic constitution. Flowering biomass yield exceeded leaf biomass yield by 7.48%, likely due to increased secondary branches during full flowering, directly impacting *T. minuta* flowering. Similarly, average floral oil content (52.04%) exceeded leaf oil content, attributed to larger oil glands and higher gland density in phyllaries compared to leaves. Flowering portion oil yield (55.16%) also surpassed leaf oil yield, owing to higher biomass and oil content at full flowering. Conversely, stem biomass yield decreased by 8.25% at full flowering compared to pre-flowering stages, possibly due to reserved material translocation from stem to floral regions during flower development. These findings are corroborated by Bansal et al. [37], Kumar et al. [38], Kumar et al. [30], Bandana et al. [39], Sood et al. [40] and Bahadirli [41]. The mass propagation of high-yield populations such as Uttarkashi, Chinyali Saur, Gangnani, and Barsu holds significant potential for essential oil production. Barsu, for example, showed the highest oil yields of 21 L ha⁻¹ in the pre-flowering stage and 44.51 L ha⁻¹ in the full-flowering stage, making it ideal for commercial cultivation. Similarly, Gangnani and Uttarkashi demonstrated high biomass and oil content, suggesting suitability for large-scale cultivation. However, challenges include maintaining consistent performance across different environmental conditions, as genotype expression can vary with soil type, altitude, and climate, potentially limiting commercial viability. Additionally, extensive propagation of a single high-yield genotype can reduce genetic diversity, increasing susceptibility to diseases and pests and potentially driving reliance on chemical interventions. To address these issues, strategies such as mixed-cultivation, adaptive breeding, and thorough environmental assessments are essential for sustainable production across varied agricultural settings.

Correlation analysis revealed strong ($p \leq 0.01$) positive correlations between plant height and biomass and oil yield at both pre-flowering and full-flowering stages. Increased plant height corresponded to higher biomass and oil yield, underscoring its importance in productivity enhancement. The positive correlation suggests that taller plants may have a larger leaf area, which can enhance photosynthesis and subsequently increase biomass production. This could result in a higher yield of essential oil as the photosynthetic capacity supports greater metabolic activity and oil synthesis. Taller plants may also support more robust flowering, leading to higher flowering oil yields. Leaf oil yield showed no significant correlation with floral oil content, whereas floral oil yield correlated significantly ($p \leq 0.05$) with leaf oil content (Table 4). The positive association between leaf length and leaf oil yield suggests that longer leaves might provide a greater surface area for photosynthesis and oil accumulation. These insights suggest that selecting plants with traits such as taller stature, larger leaf area, and more robust flowering portions could be a strategic approach to enhance oil yield

Table 3 Biomass and essential oil yield in 14 populations of *Tagetes minuta*

Populations	Pre-flowering stage				Full-flowering stage			
	Leaf portion			Stem	Flowering portion			Stem
	Fresh biomass (q ha ⁻¹)	Oil content (%)	Oil yield (l ha ⁻¹)		Fresh biomass (q ha ⁻¹)	Oil content (%)	Oil yield (l ha ⁻¹)	
Chinyali Saur	67.19 ^a	0.24 ^b	16.35 ^{bc}	338.87 ^b	66.72 ^{bc}	0.43 ^h	28.71 ^{efg}	316.77 ^a
Kalsi	44.64 ^f	0.26 ^{ab}	11.43 ^{def}	186.68 ⁱ	56.83 ^{def}	0.53 ^{cde}	30.11 ^{def}	180.62 ^{fg}
Uttarkashi	65.88 ^a	0.24 ^{bc}	15.84 ^{bc}	362.93 ^a	62.67 ^{bcd}	0.54 ^{cd}	33.86 ^c	338.11 ^a
PipaliPani	55.01 ^{cd}	0.27 ^{ab}	14.87 ^{bc}	245.76 ^d	60.94 ^{cd}	0.43 ^h	26.38 ^{fg}	193.13 ^{ef}
Sainda	40.75 ^f	0.23 ^{bc}	9.54 ^f	156.28 ^j	40.44 ^h	0.51 ^{ef}	20.64 ^h	138.47 ^h
Dolinda	48.67 ^{def}	0.20 ^c	9.73 ^f	268.97 ^c	52.59 ^{ef}	0.42 ^h	21.95 ^h	205.33 ^{de}
Palli	56.65 ^{bcd}	0.24 ^{bc}	13.49 ^{cde}	204.88 ^{gh}	62.19 ^{bcd}	0.43 ^h	26.72 ^{fg}	192.79 ^{ef}
Koti	29.32 ^g	0.20 ^c	5.77 ^g	206.50 ^g	50.35 ^{fg}	0.52 ^{de}	26.15 ^g	190.27 ^f
Gangnani	64.19 ^{ab}	0.27 ^{ab}	17.56 ^b	341.28 ^b	69.14 ^{ab}	0.57 ^b	39.64 ^b	320.10 ^a
Dandachali	57.39 ^{bc}	0.25 ^b	14.35 ^{cd}	212.16 ^{fg}	67.37 ^{abc}	0.50 ^f	33.49 ^{cd}	210.65 ^d
Mussorie	46.45 ^{ef}	0.20 ^c	9.29 ^f	237.73 ^{de}	44.87 ^{gh}	0.47 ^g	21.10 ^h	226.67 ^c
Barsu	70.55 ^a	0.30 ^a	21.00 ^a	330.94 ^b	74.18 ^a	0.60 ^a	44.51 ^a	323.67 ^b
Suwakholi	53.47 ^{cde}	0.27 ^{ab}	14.22 ^{cd}	189.02 ^{hi}	49.72 ^{fg}	0.52 ^{de}	25.90 ^g	174.04 ^h
Kaddukhal	54.70 ^{cde}	0.20 ^c	10.83 ^{ef}	228.61 ^{ef}	57.85 ^{de}	0.55 ^c	31.79 ^{cde}	210.24 ^d
Mean	53.92	0.24	13.16	250.76	58.28	0.50	29.35	230.06
CD _{0.05}	8.481	0.043	3.091	16.760	7.348	0.023	3.746	12.812

Means followed by the same letter are not significantly ($p < 0.05$) different

in commercial production. Similar correlations between morphological and yield parameters have been reported in *T. minuta* by Singhal and Srivastava [42] and Bandana [29], as well as in other species like Glory lily by Chitra and Rajamani [43], *Origanum vulgare* by Azizi et al. [44], and Iranian fennel by Bahmani et al. [45]. Geographical attributes also influenced parameter variations, despite uniform environmental conditions, with significant positive correlations observed with latitude and longitude (Table 5), suggesting their influence on population genetic constitution. Similar observations of latitude and longitude influencing leaf traits have been documented in relict tree species by Meng et al. [46] and in essential oil yield in *Lavandula latifolia* by Fernandez-Sestelo and Carrillo [47]. Wang et al. [48] reported morphological variations in *Cynodon dactylon* along longitudinal gradients.

Variability refers to variations among individuals within a plant population due to genetic or environmental factors. Genetic variability is crucial for resistance to biotic and abiotic stresses and adaptability. Effective selection relies on the presence of genetic variability. Comparison of coefficients of variation indicated lower genotypic coefficient of variation (GCV) compared to phenotypic coefficient of variation (PCV) for all studied traits, suggesting both genetic and environmental influences on trait expression. However, the marginal difference between GCV and PCV suggests a predominant role of genetic expression in trait determination. Genotypic coefficient of variation alone is insufficient for assessing heritable variations and should be complemented with heritability estimates. Traits such as plant height, collar diameter, number of main branches per plant, leaf biomass, stem biomass, and oil yield demonstrated high (> 80%) heritability, indicating minimal environmental influence and suitability for selection. Traits with high heritability and genetic gain, such as number of main branches per plant, stem biomass and oil yield from leaves and flowering parts, suggest additive gene effects controlling these traits, facilitating direct selection [49]. Medium genetic gains with high heritability were observed for collar diameter, leaf biomass, flowering biomass, and oil yield from flowering parts, indicating effective selection potential. Traits like plant height and oil content in flowering parts showed high heritability with low genetic gain, implying non-additive gene action and environmental influence (Table 6). Similar studies on genetic variability have been conducted in *T. minuta* by Singhal and Srivastava [42], Glory lily by Rajagopal and Kandhasamy [50], Iranian fennel by Izadi Darbandi et al. [51], and *T. patula* by Tamut and Singh [52].

Cluster analysis based on similarity index revealed that the Chinyali Saur, Gangnani, Uttarkashi, and Barsu cluster displays high similarity (over 90%), suggesting shared environmental conditions or genetic traits that result in a

Table 4 Simple correlation between different morphological and yield parameters in *Tagetes minuta*

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1												
2	0.617*	1											
3	0.503 ^{NS}	0.706**	1										
4	0.635*	0.608*	0.207 ^{NS}	1									
5	0.543*	0.341 ^{NS}	-0.02 ^{NS}	0.922**	1								
6	0.781**	0.729**	0.649*	0.577*	0.405 ^{NS}	1							
7	0.704**	0.871**	0.868**	0.562*	0.318 ^{NS}	0.754**	1						
8	0.481 ^{NS}	0.524 ^{NS}	0.135 ^{NS}	0.433 ^{NS}	0.343 ^{NS}	0.587*	0.260 ^{NS}	1					
9	0.755**	0.764**	0.519 ^{NS}	0.607*	0.448 ^{NS}	0.931**	0.660*	0.833**	1				
10	0.895**	0.670**	0.493 ^{NS}	0.636*	0.469 ^{NS}	0.809**	0.670**	0.603*	0.825**	1			
11	0.782**	0.854**	0.774**	0.725**	0.537*	0.779**	0.966**	0.322 ^{NS}	0.705**	0.717**	1		
12	0.224 ^{NS}	0.240 ^{NS}	0.067 ^{NS}	0.576*	0.656*	0.170 ^{NS}	0.182 ^{NS}	0.364 ^{NS}	0.300 ^{NS}	0.242 ^{NS}	0.325 ^{NS}	1	
13	0.773**	0.637*	0.422 ^{NS}	0.757**	0.670**	0.687**	0.603*	0.638*	0.770**	0.856**	0.707**	0.704**	1

* Significant at $p \leq 0.05$; ** Significant at $p \leq 0.01$; NS – Non-significant*Significant at $p \leq 0.05$; **Significant at $p \leq 0.01$; NS – Non-significant

1. Plant height (cm), 2. Collar diameter (mm), 3. No. of main branches/ plant, 4. Leaf length (cm), 5. Number of leaflets/leaf, 6. Leaf biomass at pre flowering stage (q/ha), 7. Stem biomass at pre-flowering stage (q/ha), 8. Oil content in leaf (%), 9. Oil yield in leaf (l/ha), 10. Flowering portion biomass at full-flowering stage (q/ha), 11. Stem biomass at full-flowering stage (q/ha), 12. Oil content in flowering portion (%), 13. Oil yield in flowering portion (l/ha)

Table 5 Correlation coefficient between different characteristics and three geographical variables

	1	2	3	4	5	6	7	8	9	10	11	12	13
Altitude	0.139 ^{NS}	-0.206 ^{NS}	-0.141 ^{NS}	0.152 ^{NS}	0.334 ^{NS}	0.130 ^{NS}	-0.065 ^{NS}	0.015 ^{NS}	0.106 ^{NS}	0.054 ^{NS}	0.025 ^{NS}	0.504 ^{NS}	0.317 ^{NS}
Latitude	0.267 ^{NS}	0.464 ^{NS}	0.090 ^{NS}	0.820**	0.841**	0.218 ^{NS}	0.358 ^{NS}	0.306 ^{NS}	0.321 ^{NS}	0.219 ^{NS}	0.530 ^{NS}	0.773**	0.562*
Longitude	0.595*	0.585*	0.654*	0.118 ^{NS}	-0.113 ^{NS}	0.732**	0.637*	0.397 ^{NS}	0.678**	0.693**	0.517 ^{NS}	-0.150 ^{NS}	0.450 ^{NS}

* Significant at $p \leq 0.05$; ** Significant at $p \leq 0.01$; NS – Non-significant*Significant at $p \leq 0.05$; **Significant at $p \leq 0.01$; NS – Non-significant

1. Plant height (cm), 2. Collar diameter (mm), 3. No. of main branches/plant, 4. Leaf length (cm), 5. Number of leaflets/leaf, 6. Leaf biomass at pre flowering stage (q/ha), 7. Stem biomass at pre-flowering stage (q/ha), 8. Oil content in leaf (%), 9. Oil yield in leaf (l/ha), 10. Flowering portion biomass at full-flowering stage (q/ha), 11. Stem biomass at full-flowering stage (q/ha), 12. Oil content in flowering portion (%), 13. Oil yield in flowering portion (l/ha)

high degree of relatedness. Similarly, Kalsi, Dandachalli, Palli, Suwakholi, and Sainda are grouped together, though their similarity is lower compared to the first cluster. The Koti, Mussoorie, and Kaddukhal cluster shows slightly lower similarity, indicating broader diversification or environmental separation. Finally, Pipali Pani and Dolinda, with only 40%–50% similarity form a separate subgroup and appear to be the most distinct (Fig. 3).

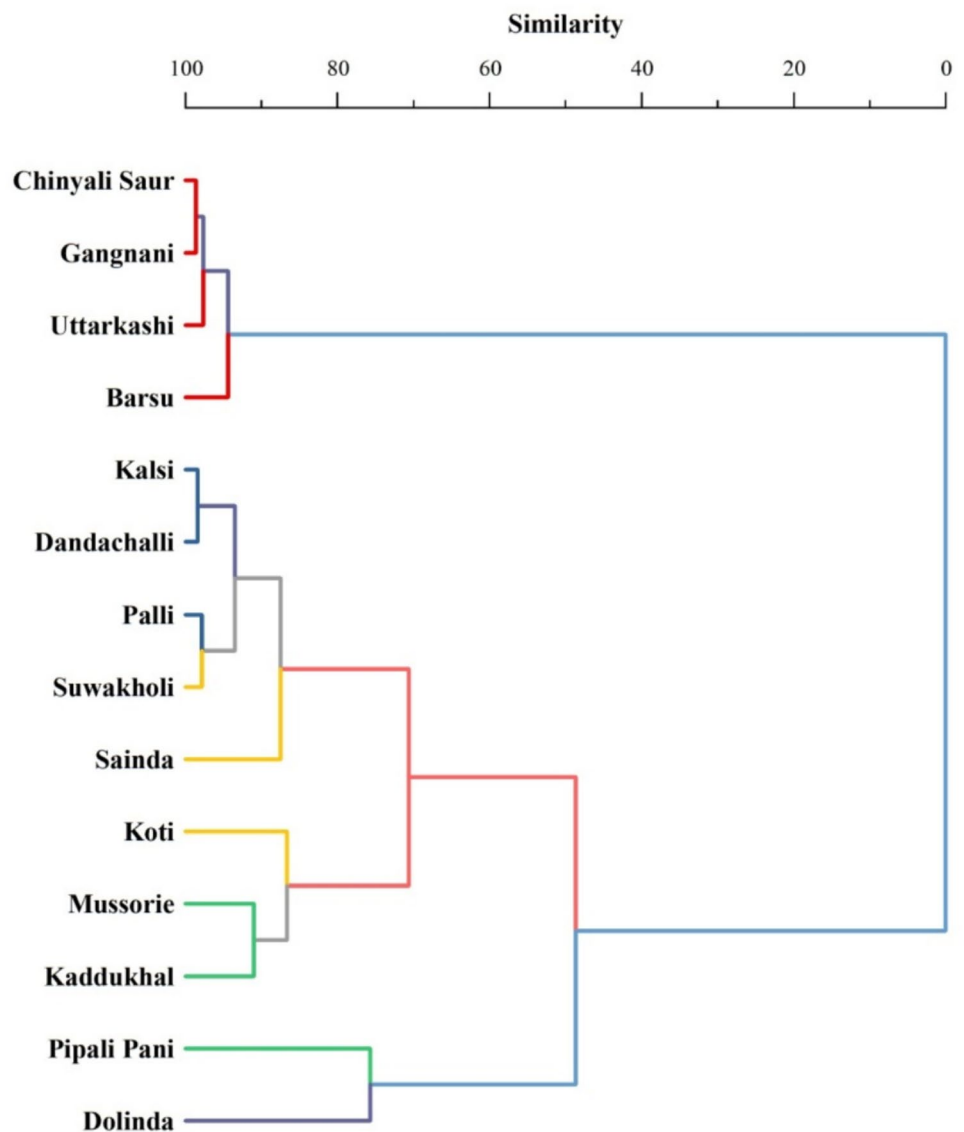
5 Conclusion

The findings of this study demonstrate the genetic potential of *T. minuta* populations from the Garhwal Himalaya for commercial essential oil production. Variation in biomass and oil yield, particularly in the flowering portion, underscores the species' suitability for targeted cultivation based on yield traits. Plant height and biomass emerged

Table 6 Estimates of phenotypic and genotypic coefficients of variability (PCV and GCV), heritability (h^2) in broad sense, and genetic gain (GG)

Parameters	PCV	GCV	h^2	GG
Plant height (cm)	9.21	8.51	85.36	16.20
Collar diameter (mm)	18.31	16.84	84.59	31.91
No. of main branches/plant	42.25	39.69	88.23	76.79
Leaf length (cm)	8.93	6.38	51.15	9.41
No. of leaflets/leaf	9.41	7.56	64.66	12.53
Leaf biomass at pre flowering stage (q/ha)	22.37	20.32	82.46	38.01
Stem biomass at pre-flowering stage (q/ha)	26.92	26.63	97.81	54.25
Oil content in leaf (%)	15.70	11.52	53.85	17.41
Oil yield in leaf (l/ha)	32.37	29.19	81.32	54.23
Flowering portion biomass at full-flowering stage (q/ha)	17.81	16.15	82.22	30.17
Stem biomass at full-flowering stage (q/ha)	28.60	28.40	98.65	58.12
Oil content in flowering portion (%)	11.77	11.44	94.45	22.90
Oil yield in flowering portion (l/ha)	24.28	23.05	90.19	45.10

Fig. 3 Hierarchical Clustering Dendrogram of Population Similarity Based on Percentage Similarity Index



as crucial indicators of oil yield, essential for selecting high-yielding germplasm. Although qualitative morphological traits were consistent, the observed genetic variability, alongside environmental influences such as geographical location, provides important insights for breeding and cultivation strategies. Populations exhibiting high heritability and genetic gain in traits like oil yield should be prioritized for commercial production. However, scaling up cultivation must consider potential ecological risks and the importance of maintaining genetic diversity to ensure long-term sustainability. These insights advocate for breeding programs focused on populations with strong additive gene effects and high heritability to maximize yield potential while preserving ecological balance. Our findings underscore substantial variation in morphological traits such as plant height, primary branches, and leaf characteristics, alongside pivotal yield parameters including biomass and oil content. These variations, predominantly governed by genetic factors, highlight the species' adaptability and potential for selective breeding to enhance productivity and quality traits. The Barsu population displayed the highest values in biomass and essential oil yield, suggesting it as a superior candidate for further genetic and phytochemical investigations aimed at maximizing economic returns. Plant height and biomass emerged as crucial indicators of oil yield, essential for selecting high-yielding germplasm. The correlation between plant height and oil yield, underscores the importance of these traits in breeding programs. Geographical influences on plant characteristics highlight potential regional variations, emphasizing the necessity for location-specific evaluations in future breeding efforts.

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Data availability The data taken and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability Not applicable.

Declarations

Ethics approval and consent to participate The plant materials used in the present study were collected from various locations in Uttarakhand. The experimental protocols were approved by the V.C.S.G. Uttarakhand University of Horticulture and Forestry, Bharsar. The sample collection is duly permitted and approved by the university.

Competing interests The authors declare no competing interests.

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