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# Morphological diversity among different populations of Grewia optiva J.R. Drumm. Ex Burret in Western Himalaya, India

**Anjali Sharma**[1] and **Varun Attri**[2*]

[1]*Punjab Agricultural University, Department of Forestry and Natural Resources, Ludhiana-141004, Punjab*
[2]*Punjab Agricultural University, Regional Research Station, Ballowal Saunkhri, Balachaur, SBS Nagar- 144521, Punjab*

* Corresponding author. E-mail: attrivarun86@pau.edu

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ABSTRACT

Grewia optiva is an important multipurpose tree species widely distributed in the Northwestern Himalayas. The present study aimed to assess eco-geographical variation in growth, leaf, and fruit traits across Punjab and Himachal Pradesh, India. The field surveys were conducted at twelve sites located in Hoshiarpur and Shaheed Bhagat Singh Nagar districts of Punjab and Una and Solan districts of Himachal Pradesh. At each site, trees were categorized into three diameter classes (10-20 cm, 20-30 cm, and >30 cm), with a minimum of five trees sampled per class. The significant variation was observed among locations for most traits. The plant height ranged from 3.38 m at Ballowal Saunkri to 12.72 m at Nauni. The maximum crown spread was recorded at Nauni (4.74 m) and Janauri (4.73 m). The number of primary branches did not differ significantly among locations. The secondary branches showed significant variation, with values ranging from 5.33 at Badwar to 13.67 at Dholwaha. The primary branch angle ranging from 26.33° at Bhaddi to 46.67° at Dehni. Leaf traits also varied considerably, maximum leaf length (13.86 cm), Leaf width (7.32 cm), leaf area (45.62 cm$^2$), maximum fresh weight (76.59 g) and dry weight (38.09 g) of 100 leaves were recorded at Nauni. Fruit characteristics also showed significant variability; Fresh and dry weights of leaves were highest at Nauni and lowest at Ballowal Saunkri. Fruit traits also differed significantly; maximum fruit length (5.06 mm), width (4.30 mm), and dry weight (13.54 g) were recorded at Nauni, while Lambalahri showed maximum fruit thickness (4.20 mm) and fresh weight (21.88 g). Higher diameter classes (D2 and D3) consistently exhibited superior growth and biomass traits compared to D1. Correlation analysis revealed strong positive associations among growth, leaf, and biomass parameters. The study highlights substantial phenotypic variability and identifies Nauni, Kailar, and Gaura as superior populations for selection and genetic improvement.

## INTRODUCTION

*Grewia optiva* (J.R. Drumm. ex Burret) (family Malvaceae; formerly Tiliaceae) is an important multipurpose agroforestry tree species commonly known as biul, bihul, bhimal, or dhaman, this species is widely cultivated along the bunds of agricultural fields between 500 and 2500 m elevation across the Northwestern Himalayas and the hilly tracts of southern India and Myanmar (Murasing *et al.*, 2022). In Indian subcontinent, it occurs naturally in India, Nepal, Bhutan, and Pakistan (Bhagta *et al.*, 2019). In India, it is distributed across Himachal Pradesh, Uttarakhand, Jammu and Kashmir, Punjab, and Sikkim. *G. optiva* thrives under a broad range of environmental conditions preferring sandy loam soils with moderate moisture but capable of growing in varied soil types and tolerates temperatures between - 2°C and 38°C and annual rainfall from 1200 to 2500 mm (Luna, 1996; Orwa *et al*., 2009). *G. optiva* is a small to medium-sized deciduous tree (13-15 m tall; 0.8-1.0 m diameter), characterized by a thick ashy-white exfoliating bark and rough, stellate-hairy young shoots (Sankhyan *et al*., 2020a). The leaves are opposite, petiolate, and ovate to broadly ovate, while the inflorescences are cymose with one to eight pale yellow or white flowers, blooming simultaneously with leaf flush during April-May (Orwa *et al*., 2009). Its drupe fruit turns from olive-green to black upon maturation and is edible both raw and cooked (Heuzé *et al*., 2019). Leaf shedding typically occurs in March- April, followed by fruit maturity in September and ripening by December (Chauhan *et al*., 2021). The species tolerates frost and drought but is susceptible to fire and grazing pressures (Katoch *et al*., 2017; Singh *et al*., 2018). The ecologically and economically, *G. optiva* is one of the most valuable farmer-friendly agroforestry trees of the Northwestern Himalayas (Verma, 2015). It is highly preferred on agricultural field boundaries due to multiple beneficial attributes:

(i) production of high-quality, palatable green fodder during winter fodder scarcity months; (ii) strong coppicing ability (Sankhyan & Bhagta, 2016; Mukherjee *et al*., 2018; Sahoo *et al*., 2016; Gachuiri *et al*., 2017); (iii) substantial litter contribution enhancing soil fertility (Kar *et al*., 2019); and (iv) fiber-producing branches used for making ropes and other household products. Fiber-yielding plant species such as *G. optiva* rank second in economic importance after food crops in India (Pandey and Gupta, 2003; Negi *et al*., 2010). Mature trees can produce 12–30 kg of leaf fodder annually (Sankhyan *et al*., 2022), with high crude protein content (17.4–21.0 %) and >70% dry matter digestibility, making it a vital nutrient source for livestock (Bhagta & Sankhyan, 2016; Verma *et al*., 2014). Nutritional quality, however, varies seasonally, with higher protein levels recorded in young and winter leaves relative to those in the rainy season. *G. optiva* is not a common forest species, its occurrence near villages and agricultural terraces underscores its adaptation to human-managed landscapes. Its broad elevational range indicates strong ecological adaptability to variable microclimatic and edaphic conditions. Such altitudinal and environmental heterogeneity can exert differential selection pressures on morphological and physiological traits, leading to local adaptation. Moreover, its capacity to regenerate rapidly after pruning contributes to biomass accumulation and carbon storage (Rana *et al*., 2020). Given its wide ecological amplitude, high fodder and fiber value, and critical role in sustaining agroforestry systems, assessing morphological variation among natural populations of *G. optiva* is essential. Understanding such intraspecific variability forms the scientific basis for selection of superior genotypes for breeding and tree improvement programs. Therefore, the present study aims to evaluate the morphological diversity of *G. optiva* across different populations of the North-Western Himalaya to identify variants with desirable traits for genetic improvement and sustainable utilization.

## MATERIALS AND METHODS

### *Study Area*

In Punjab, the study sites included Hoshiarpur and Shaheed Bhagat Singh (SBS) Nagar districts, whereas in Himachal Pradesh, sampling was undertaken in Una and Solan districts (Table 1). The survey aimed to assess the morphological variation in *Grewia optiva* populations and to identify representative stands for

subsequent evaluation. *Grewia optiva* is not a common forest tree but occurs naturally along field bunds and margins. Therefore, sample trees were randomly selected from farmlands across the chosen locations to ensure adequate population coverage.

### *Data Collection*

Morphological observations were recorded on twelve population site, at each site, trees were categorized into three diameter classes (10-20 cm (D1), 20-30 cm (D2), and >30 cm (D3), with a minimum of five trees sampled per class were randomly selected to represent intra-population variability. The Tree level traits measured included tree height, DBH, crown spread, and the number of primary and secondary branches. Tree height was measured using a Ravi altimeter, while DBH was determined using an aluminium caliper. Crown spread was measured along two perpendicular directions and averaged. The number of primary branches emerging from the main stem and the number of secondary branches were counted directly, and primary branch angles were measured following standard field procedures. Variation in leaf characteristics among populations was analyzed following the standard statistical methodologies of Robinson *et al*. (1951) and Al-Jibouri *et al*. (1958). Leaf sampling was carried out during November- December. Leaves were collected from the entire crown of each selected tree, covering different canopy positions (top, middle, and base). To capture size variability, ten fully expanded leaves from each size category were sampled per tree. Only healthy leaves free from pathogen infection, herbivore damage, or epiphyllic cover were used. Immediately after collection, leaves were wrapped in a moist cloth to prevent dehydration and shrinkage, and transported to the laboratory for analysis. The following leaf traits were measured: leaf length (cm), leaf width (cm), leaf area ($cm^2$), and petiole length (cm). Leaf area was determined using a leaf area meter. Fruit samples were collected from the same trees used for morphological observations. Fruit characteristics measured included fruit length, width, thickness, fresh weight, and dry weight. Fruit measurement procedures followed the methodology of Kaushal (1978).

## RESULTS AND DISCUSSION

### *Tree characteristics*

The significant variation was observed among different locations for most of the tree characters studied. The plant height ranged from 3.38 m at Ballowal Saunkri (S4) to 12.72 m at Nauni (S11). The tallest plants were recorded at Nauni S11 (12.72 m) and Kailar S12 (11.20 m), which were statistically at par with each other, while Gaura (S10) (9.80 m) and Badwar (S8) (8.16 m) also recorded significantly higher plant height compared to other locations. The minimum plant height was observed at Ballowal Saunkri (S4) (3.38 m), followed by Dehni (S6) (3.60 m) and Bhaddi (S5) (3.68 m). The crown spread ranged from 2.17 m at Ballowal Saunkri (S4) to

4.74 m at Nauni (S11). The maximum crown spread was recorded at Nauni (S11) (4.74 m) and Janauri (S2) (4.73 m), which were statistically at par, followed by Dehni (S6) (4.57 m) and Dholwaha (S3) (4.28 m). The minimum crown spread was observed at Ballowal Saunkri (S4) (2.17 m). The number of primary branches

did not differ significantly among locations. However, numerically, the highest number of primary branches was recorded at Nauni (S11) (5.80), followed by Dehni (S6) and Gaura (S10) (5.40 each), while the minimum number was observed at Janauri (S2) (3.80). The secondary branches showed significant variation, with values ranging from 5.33 at Badwar (S8) to 13.67 at Dholwaha (S3). The maximum number of secondary branches was recorded at Dholwaha (S4) (13.67), which was significantly higher than most locations and at par with Ballowal Saunkri (S4) (12.00) and Nauni (S11) (11.67). The minimum number of secondary branches was observed at Badwar (S8) (5.33), followed by Dehni (S6) (6.33) and Lambalahri (S9) and Kailar (S12) (6.67 each). The primary branch angle ranging from 26.33° at S5 to 46.67° at S6. The widest branch angle was recorded at S6 (46.67°), which was statistically at par with S3 and S11 (41.67° each), while the narrowest branch angle was observed at S5 (26.33°) and S8 (26.67°) (Table 2).The interaction between diameter classes and population

### *Leaf characteristics*

The significant variation was observed among locations for most of the leaf characteristics. The leaf length ranged from 9.14 cm at Patiari (S1) to 13.86 cm at Nauni (S11). The maximum leaf length was recorded at Nauni (S11) (13.86 cm), which was statistically at par with Kailar (S12) (13.18 cm) and Gaura (S10) (12.94 cm), followed by Lambalahri (S9) (12.60 cm). The minimum leaf length was observed at Patiari S1 (9.14 cm), which was statistically similar to Janauri S2 (9.98 cm) and Bhaddi S5 (9.96 cm). The widest leaves width was recorded at Nauni S11(7.32 cm), which was statistically at par with Kailar S12 (7.08 cm) and Gaura S10 (6.98 cm). The minimum leaf width was observed at Patiari S1 (5.26 cm) and Janauri S2 (5.28 cm). The maximum leaf area was recorded at Nauni S11 (45.62 $cm^2$), which was significantly higher than most locations and at par with Kailar S12 (43.46 $cm^2$). Higher leaf area was also observed at Gaura S10 (41.72 $cm^2$) and Lambalahri S9 (40.80 $cm^2$). The minimum leaf area was recorded at Patiari S1 (30.80 $cm^2$). The Petiole however, numerically, the highest petiole length was observed at Janauri S2 (1.10 cm), while the minimum values were recorded at Bangana S7 and Gaura S10 (0.92 cm each). The maximum fresh weight was recorded at Nauni S11 (76.59 g), which was statistically at par with Dholwaha S3 (74.22 g) and Gaura S10 (72.42 g). The minimum fresh weight was observed at Ballowal Saunkri S4 (50.85 g).The dry weight of 100 leaves also varied significantly across locations, ranging from 22.95 g at Ballowal Saunkri S4 to 38.09 g at Nauni S11. The highest dry weight was recorded at Nauni S11 (38.09 g), followed by Gaura S10 (34.53 g) and Dehni S6 (31.12 g), while the lowest dry weight was observed at Ballowal Saunkri S4 (22.95 g) and Patiari S1 (24.06 g) (Table 3).

The interaction between diameter classes and population sites showed that diameter classes (D2) recorded greater values for Leaf length, leaf width, Leaf area, Petiole length and fresh and dry weight of 100 leaves followed by D3 and minimum in D1. Among the population sites, S10 and S12 generally exhibited higher values for most parameters, indicating better growth performance at these locations (Fig 2. a-e). These variations align with previous studies, which attribute leaf morphological differences to environmental factors such as altitude, temperature, and nutrient availability (Thakur *et al.*, 2022). Leaf traits are known to adapt to local environmental conditions, as observed by Sankhyan *et al.* (2019) in *Grewia optiva*, where significant differences in leaf area and petiole length were reported across different sites. The influence of altitude on leaf morphology has also been demonstrated in *Quercus* species, where leaf size decreases with increasing altitude (Singh *et al.*, 2021b). Sharma and Gupta (2018) further highlighted the role of temperature, light availability, and soil nutrients in determining leaf traits in *Toona ciliata*. Since leaf size influences key physiological processes like photosynthesis, transpiration, and respiration, it is closely linked to environmental adaptations (Leigh *et al.*, 2017). Similar findings by Sankhyan *et al.* (2020) in *Grewia optiva* reported a leaf length range of 8.94-

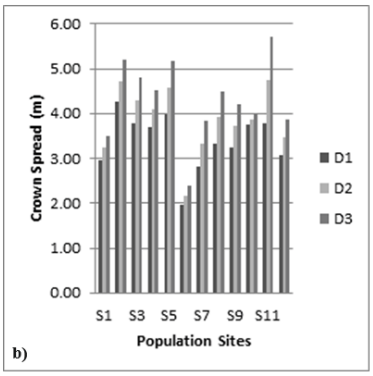


**Figure 2.** Fig. 1. Interaction effects of tree characteristics between diameter classes and population sites: (a) plant height, (b) crown spread, (c) primary branches, (d) secondary branches, and (e) primary branch angle.

15.87 cm, leaf width of 5.36–9.88 cm, and leaf area of

44 . 95 - 123 . 49 $cm^2$, reinforcing the current observations. Additionally, Thakur *et al.* (2022) noted maximum leaf length (17.38 cm) and width (11.6 cm) in clone HA-4 and the highest leaf area (129.89 $cm^2$) in clone HA-2 of *Grewia optiva*. The present findings are further supported by the works of Bhagta (2015), Sankhyan

*et al*

(2019), and Thakur (2021), demonstrating significant diversity in leaf traits within

*Grewia optiva*.

### *Fruit characters*

The study revealed significant variations in fruit morphological traits across different locations, including fruit length, width, thickness, fresh weight, and dry weight (Table 4). The maximum fruit length (5.06 mm) was recorded at S11, which was statistically similar to S12 (4.94 mm), S10 (4.86 mm), S9 (4.82 mm), and S8 (4.96 mm), whereas the shortest was observed at S1 (3.68 mm), comparable to S5 (3.82 mm). Similarly, the highest fruit width was recorded at S11 (4.30 mm), followed by S12 (3.94 mm) and S10 (3.96 mm), while the smallest was at S2 (3.08 mm). The maximum fruit thickness was found at S9 (4.20 mm), which was statistically similar to S11 (4.02 mm) and S10 (3.98 mm), whereas the lowest was observed at S4

(3.22 mm). The highest fresh fruit weight (21.88 g) was recorded at Lambalahri S9, which was statistically at par with S10 (21.52 g) and S11 (21.84 g), whereas the lowest was found at S1 (20.04 g). The highest dry fruit weight was recorded at S11 (13.54 g), comparable to several other locations, while the lowest was at S6 (11.76 g) (Table 4). The interaction between diameter classes and locations showed a consistent increasing trend in all fruit parameters. Fruit length, width, thickness, fresh weight, and dry weight increased progressively from D1 to D3 across all locations,

**Table 3: Morphological variations in Leaf characteristics among different locations of *Grewia optiva***

| Locations | Leaf characteristics | | | | | |
|---|---|---|---|---|---|---|
| | Leaf length | Leaf width | Leaf area | Petiole length | Fresh Weight of 100 Leaves (g) | Dry Weight of 100 Leaves (g) |
| Patiari | 9.14 ± 1.50f | 5.26 ± 1.93e | 30.8 ± 1.64g | 1.06 ± 0.26a | 64.68±0.62ab | 24.06±0.35h |
| Janauri | 9.98 ± 0.87f | 5.28 ± 0.65e | 35.8 ± 2.05f | 1.10 ± 0.12a | 70.80±2.81ab | 30.447±0.38d |
| Dholwaha | 11.56 ± 0.72e | 5.86 ± 0.65cde | 36.4 ± 2.07ef | 1.02 ± 0.08a | 74.22±3.72a | 27.947±0.22f |
| Bhaddi | 9.96 ± 0.62f | 5.54 ± 0.35e | 37.6 ± 2.07def | 1.02 ± 0.11a | 61.06±8.08bc | 28.057±0.09f |
| Tibba Nangal | 11.16 ± 1.01e | 5.58 ± 0.40de | 38.2 ± 1.92cdef | 0.94 ± 0.11a | 69.84±9.26ab | 31.117±0.45c |
| Ballowal Saunkri | 11.4 ± 0.76e | 6.4 ± 0.28bcd | 39.6 ± 0.89cde | 1.08 ± 0.15a | 50.85±2.56c | 22.947±0.16i |
| Bangana | 11.82 ±1.16de | 6.56 ± 0.40abc | 40.16 ± 6.86bcd | 0.92 ± 0.13a | 70.34±8.72ab | 30.367±0.40d |
| Badwar | 12.12 ± 0.92cde | 6.72 ± 0.23ab | 40.48 ± 2.72bcd | 0.94 ± 0.06a | 61.08±3.20bc | 25.337±0.26g |
| Lambalahri | 12.60 ± 0.19bcd | 6.58 ± 0.67abc | 40.8 ± 0.98bcd | 1.06 ± 0.17a | 65.93±3.66ab | 25.7±0.21g |
| Gaura | 12.94 ± 0.61abc | 6.98 ± 0.36ab | 41.72 ± 2.96bc | 0.92 ± 0.21a | 72.42±10.60ab | 34.53±0.50b |
| Nauni | 13.86 ± 0.26ba | 7.32 ± 0.18a | 45.62 ± 0.55a | 0.98 ± 0.16a | 76.59±10.79a | 38.087±0.49a |

| | | | | | | |
|---|---|---|---|---|---|---|
| Kailar | 13.18 ± 0.30ab | 7.08 ± 0.27ab | 43.46 ± 2.90ab | 0.94 ± 0.15a | 67.94±7.19ab | 29.53±0.34e |
| CD (0.05) | 1.04 | 0.85 | 3.55 | NS | 10.44 | 0.39 |

**Table 4: Morphological variations in fruit characteristics among different locations of *Grewia optiva***

| Locations | Fruit length | Fruit width | Fruit thickness | Fresh weight of fruits (100 g) | Dry weight of fruits (100 g) |
|---|---|---|---|---|---|
| Patiari | 3.68 ± 0.26f | 3.08 ± 0.25f | 3.44 ± 0.42cd | 20.04 ± 0.22e | 12.76 ± 0.15bc |
| Janauri | 4.22 ± 0.426d | 3.34 ± 0.34def | 3.92 ± 0.16ab | 20.82 ± 0.08bc | 12.82 ± 0.19bc |
| Dholwaha | 4.46 ± 0.39cd | 3.56 ± 0.42cde | 3.98 ± 0.13ab | 21.58 ±0.29ab | 13.02 ± 0.16abc |
| Bhaddi | 3.82 ± 0.26ef | 3.24 ± 0.21ef | 3.96 ± 0.18ab | 21.58 ±0.27ab | 13.26 ± 0.33ab |
| Tibba Nangal | 4.18 ± 0.31de | 3.38 ± 0.35def | 3.86 ± 0.06abc | 21.42 ± 0.23b | 11.76 ± 1.06d |
| Ballowal saunkri | 4.4 ± 0.39d | 3.66 ± 0.45cde | 3.22 ± 0.34d | 20.3 ± 0.55de | 12.86 ± 0.20abc |
| Bangana | 4.52 ± 0.57bcd | 3.72 ± 0.56bcd | 3.68 ± 0.46bc | 20.36 ± 0.50de | 12.56 ± 1.06c |
| Badwar | 4.96 ± 0.15a | 4.16 ± 0.38ab | 3.94 ± 0.23ab | 20.88 ±0.045c | 13.32 ± 0.55ab |
| Lambalahri | 4.82 ± 0.19abc | 4.14 ± 0.29ab | 4.2 ± 0.20a | 21.88 ± 0.08a | 13.00 ± 0.20abc |
| Gaura | 4.86 ± 0.22ab | 3.96 ± 0.39abc | 3.98 ± 0.41ab | 21.52 ±0.33ab | 13.12 ± 0.40abc |
| Nauni | 5.06 ± 0.11a | 4.3 ± 0.25a | 4.02 ± 0.51ab | 21.84 ± 0.06a | 13.54 ± 0.36a |
| kailar | 4.94 ± 0.06a | 3.94 ± 0.11abc | 3.76 ± 0.37bc | 20.54 ± 0.35cd | 13.08 ± 0.52abc |
| CD (0.05) | 0.39 | 0.47 | 0.42 | 0.37 | 0.68 |

and Badwar. The differences were statistically significant, confirming a strong interaction effect between diameter class and location on fruit characteristics (Table 5). These variations can be attributed to differences in environmental conditions, genetic potential and site-specific factors influencing fruit development. Similar findings were reported by Sankhyan *et al.* (2020), who observed significant variability in *Grewia optiva* fruit characteristics, with fruit length ranging from 5.50–6.25 mm, fruit width from 4.61–5.10 mm, fruit thickness from 4.32–5.40 mm, fresh weight of 100 fruits between 20.01–23.31 g, and dry weight from 12.27–15.44g. Thakur *et al.* (2022) further highlighted genetic variations in different clones, where clone SI-10 exhibited the highest fresh fruit weight (22.17 g) and clone CH-3 had the maximum dry weight (15.56 g). Similar trends were also reported by Bhagta (2015) and Bhatt (2010) in *Grewia optiva*, as well as by Sankhyan *et al.*, (2019) and Bhagta *et al.* (2015) in open-pollinated seedling seed orchards of *Grewia optiva*.

### *Correlation and Principal component analysis Studies*

The correlation analysis revealed strong positive associations among growth and biomass-related traits (Fig. 3). Plant height (PH) was positively correlated with leaf length (LL), leaf width (LW), leaf area (LA), and biomass parameters such as fresh weight (FW) and dry weight (DW), indicating that increased plant stature is associated with enhanced leaf development and biomass accumulation. Leaf traits (LL, LW, and LA) were also highly intercorrelated, reflecting their combined contribution to canopy growth. Fresh and dry weights, both at leaf and whole- plant levels, exhibited significant positive correlations, suggesting consistency in biomass production. In contrast, traits such as peitole length (PL) and certain structural parameters showed weak to negative correlations with major growth traits, indicating independent or inverse relationships. The results are in accordance with the studies of Singh *et al.*, (2012) who observed that, early selection criteria in tree improvement programs are strongly influenced by genetic correlations, indicating that enhancing one trait will positively impact others. Principal component analysis (PCA) effectively summarized the multivariate variation among the studied traits into two principal components, with PC1 accounting for the largest proportion of total

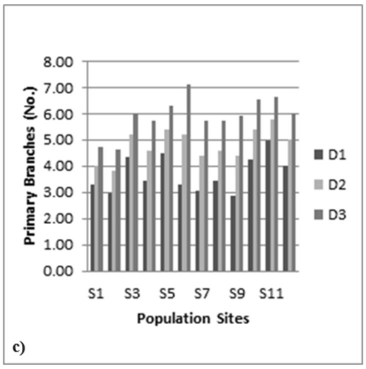


**Figure 3.** Fig. 1. Interaction effects of tree characteristics between diameter classes and population sites: (a) plant height, (b) crown spread, (c) primary branches, (d) secondary branches, and (e) primary branch angle.

**Table 5: Interaction effects in Fruit characteristics between diameter classes and population sites**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dry wt (100 g)** | **D3** | 12.91 | 13.01 | 13.18 | 13.59 | 12.82 | 13.06 | 13.62 | 13.87 | 13.20 | 13.52 | 13.90 | 13.60 | 0.61 |
| | **D2** | 12.76 | 12.82 | 13.02 | 13.26 | 11.76 | 12.86 | 12.56 | 13.32 | 13.00 | 13.12 | 13.54 | 13.08 | |
| | **D1** | 12.61 | 12.63 | 12.86 | 12.93 | 10.70 | 12.66 | 11.50 | 12.77 | 12.80 | 12.72 | 13.18 | 12.56 | |
| **Fresh wt (100 g)** | **D3** | 20.26 | 20.90 | 21.87 | 21.85 | 21.65 | 20.85 | 20.86 | 20.93 | 21.96 | 21.85 | 21.90 | 20.89 | 0.82 |
| | **D2** | 20.04 | 20.82 | 21.58 | 21.58 | 21.42 | 20.30 | 20.36 | 20.88 | 21.88 | 21.52 | 21.84 | 20.54 | |
| | **D1** | 19.82 | 20.74 | 21.29 | 21.31 | 21.19 | 19.75 | 19.86 | 20.84 | 21.80 | 21.19 | 21.78 | 20.19 | |
| **Fruit thickness (mm)** | **D3** | 3.86 | 4.08 | 4.11 | 4.14 | 3.92 | 3.56 | 4.14 | 4.17 | 4.40 | 4.39 | 4.53 | 4.13 | 0.32 |
| | **D2** | 3.44 | 3.92 | 3.98 | 3.96 | 3.86 | 3.22 | 3.68 | 3.94 | 4.20 | 3.98 | 4.02 | 3.76 | |
| | **D1** | 3.02 | 3.76 | 3.85 | 3.78 | 3.80 | 2.88 | 3.22 | 3.71 | 4.00 | 3.57 | 3.51 | 3.39 | |
| **Fruit width (mm)** | **D3** | 3.33 | 3.68 | 3.98 | 3.45 | 3.73 | 4.11 | 4.28 | 4.54 | 4.43 | 4.35 | 4.55 | 4.05 | 0.29 |
| | **D2** | 3.08 | 3.34 | 3.56 | 3.24 | 3.38 | 3.66 | 3.72 | 4.16 | 4.14 | 3.96 | 4.30 | 3.94 | |
| | **D1** | 2.83 | 3.00 | 3.14 | 3.03 | 3.03 | 3.21 | 3.16 | 3.78 | 3.85 | 3.57 | 4.05 | 3.83 | |
| **Fruit length (mm)** | **D3** | 3.94 | 4.65 | 4.85 | 4.08 | 4.49 | 4.79 | 5.09 | 5.11 | 5.01 | 5.08 | 5.17 | 5.00 | 0.35 |
| | **D2** | 3.68 | 4.22 | 4.46 | 3.82 | 4.18 | 4.40 | 4.52 | 4.96 | 4.82 | 4.86 | 5.06 | 4.94 | |
| | **D1** | 3.42 | 3.79 | 4.07 | 3.56 | 3.87 | 4.01 | 3.95 | 4.81 | 4.63 | 4.64 | 4.95 | 4.88 | |
| **Parameter Diameter Population sites** | | Patiari | Janauri | Dholwaha | Bhaddi | Tibba Nangal | Ballowal Saunkri | Bangana | Badwar | Lambalahri | Gaura | Nauni | Kailar | C D (P = 0.05) |

variability, followed by PC2 (Fig. 4). The biplot revealed that PC1 was primarily driven by growth and biomass-associated traits, including plant height (PH), leaf length (LL), leaf width (LW), fresh weight (FW), and dry weight (DW), which were strongly and positively loaded on the positive axis. The close clustering and acute angles among these vectors indicate a high degree of positive correlation,

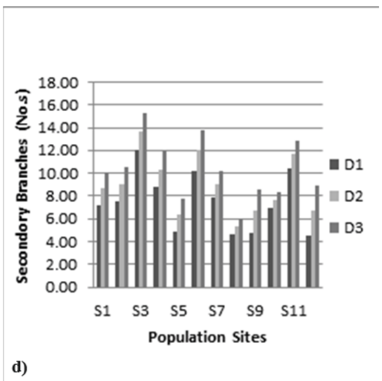


**Figure 4.** Fig. 1. Interaction effects of tree characteristics between diameter classes and population sites: (a) plant height, (b) crown spread, (c) primary branches, (d) secondary branches, and (e) primary branch angle.

suggesting that these traits collectively contribute to overall plant vigor and productivity.

Similarly, Bhagta and Sankhyan (2016) reported a strong genotypic (0.22) and phenotypic (0.17) correlation between 100 dry fruit weight and 100 seed weight in the seedling seed orchard of *Grewia optiva*. Mehta *et al*. (2022) also found strong positive correlations between collar diameter and fresh fodder

weight, as well as between diameter at breast height, collar diameter, fresh fodder weight, and fuelwood weight in *Grewia optiva* clones from the lower Shivalik Himalayas. Thakur *et al.* (2022) observed strong positive correlations between growth traits and fresh fruit weight, while dry fruit weight correlated positively with seed weight and negatively with leaf dry matter content.

## CONCLUSION

The study revealed significant variations in tree, leaf, and fruit traits of *Grewia optiva* across different locations, influenced by environmental conditions and genetic factors. Nauni exhibited the highest tree growth, leaf size, and fruit dimensions, while Ballowal Saunkhri and Patiari recorded the lowest values. Strong correlations were observed between plant height, diameter, leaf traits, and fruit characteristics, indicating their interconnected growth patterns. PCA identified key traits contributing to variability, with leaf and fruit dimensions being the most influential. This finding highlights substantial phenotypic variability and identifies Nauni, Kailar, and Gaura as superior populations for selection and genetic improvement programs, selection of superior genotypes, and sustainable plantation management.

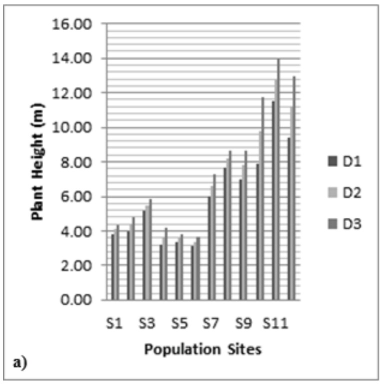


**Figure 1.** Fig. 1. Interaction effects of tree characteristics between diameter classes and population sites: (a) plant height, (b) crown spread, (c) primary branches, (d) secondary branches, and (e) primary branch angle.

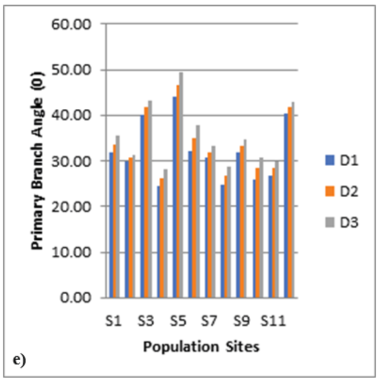


**Figure 5.** Fig. 1. Interaction effects of tree characteristics between diameter classes and population sites: (a) plant height, (b) crown spread, (c) primary branches, (d) secondary branches, and (e) primary branch angle.

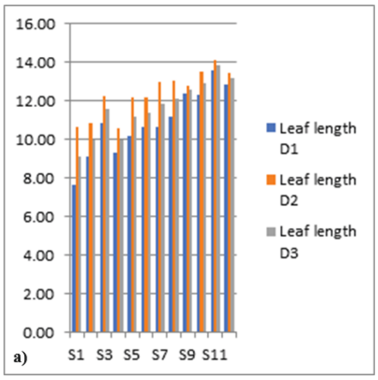


**Figure 6.** Fig. 2. Interaction effects in Leaf characteristics between diameter classes and population sites: (a) Leaf length, (b) Leaf width, (c) Leaf area , (d) petiole length , (e) Fresh weight and (f) Dry weight.

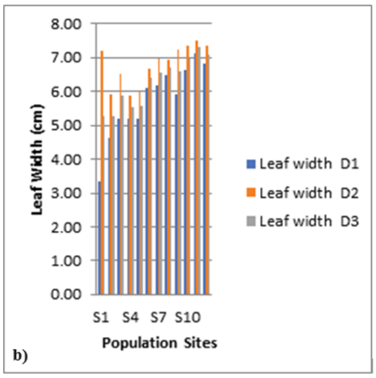


**Figure 7.** Fig. 2. Interaction effects in Leaf characteristics between diameter classes and population sites: (a) Leaf length, (b) Leaf width, (c) Leaf area , (d) petiole length , (e) Fresh weight and (f) Dry weight.

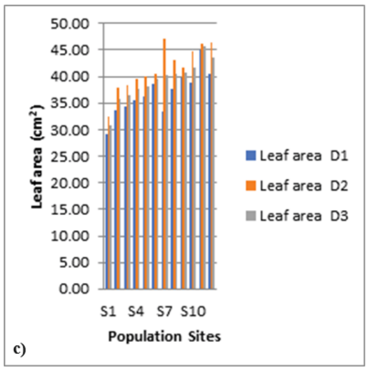


**Figure 8.** Fig. 2. Interaction effects in Leaf characteristics between diameter classes and population sites: (a) Leaf length, (b) Leaf width, (c) Leaf area , (d) petiole length , (e) Fresh weight and (f) Dry weight.

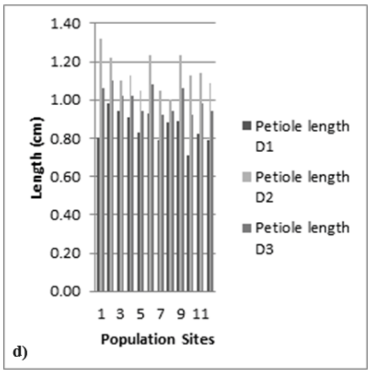


**Figure 9.** Fig. 2. Interaction effects in Leaf characteristics between diameter classes and population sites: (a) Leaf length, (b) Leaf width, (c) Leaf area , (d) petiole length , (e) Fresh weight and (f) Dry weight.

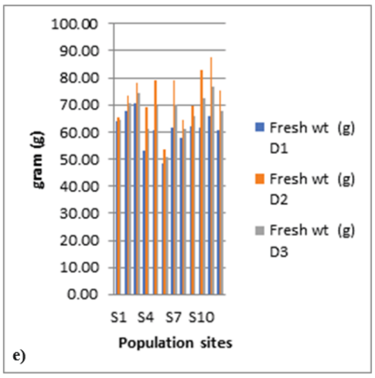


**Figure 10.** Fig. 2. Interaction effects in Leaf characteristics between diameter classes and population sites: (a) Leaf length, (b) Leaf width, (c) Leaf area , (d) petiole length , (e) Fresh weight and (f) Dry weight.

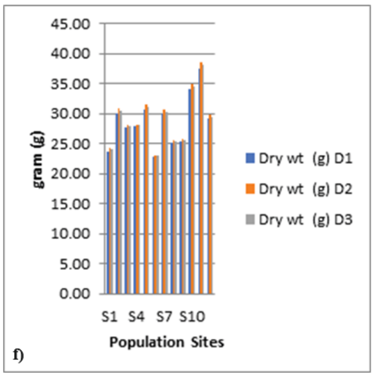


**Figure 11.** Fig. 2. Interaction effects in Leaf characteristics between diameter classes and population sites: (a) Leaf length, (b) Leaf width, (c) Leaf area , (d) petiole length , (e) Fresh weight and (f) Dry weight.

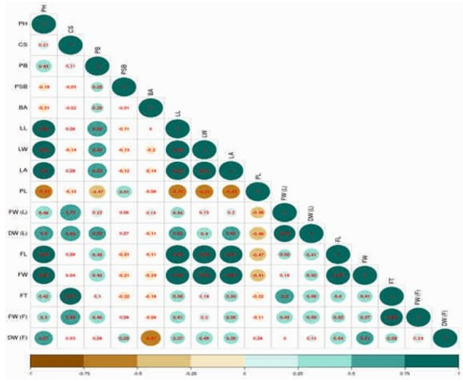

**Figure 12.** Fig.3 Correlation matrix (Pearson's r) showing relationships among tree growth, leaf and fruit traits,

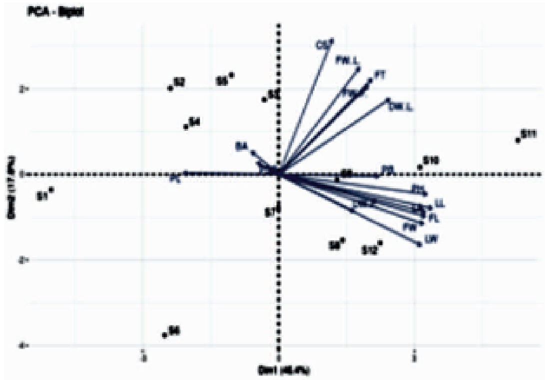


**Figure 13.** Fig 4. Principal Component Analysis (PCA) showing relationships among tree growth, leaf, and fruit traits

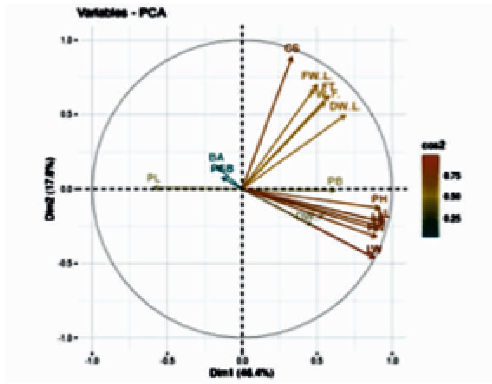


**Figure 14.** Fig 4. Principal Component Analysis (PCA) showing relationships among tree growth, leaf, and fruit traits

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