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Provenance-based Variation in Seed Traits of *Quercus leucotrichophora* A. Camus in Western Himalayas

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Abstract: The present study investigated provenance variation in seed characteristics of *Quercus leucotrichophora* A. Camus (Ban Oak) across fifteen distinct locations in Western Himalayas of Himachal Pradesh. Mature acorns were collected from phenotypically superior trees representing altitudinal gradients ranging from 1220 m to 2206 m above mean sea level. Key seed traits such as acorn length, width, moisture content, and 100-seed weight were analyzed. Significant variation was observed among provenances and seed size categories. These traits are important for improving the planting stock material in hand. The largest acorn size (2.28 cm length, 1.21 cm width), highest moisture content (63.87%), and maximum 100-seed weight (239.15 g) was at Haripurdhar (P_9), the highest elevation site. Seed size grading revealed that large seeds (S_3) consistently showed superior physical attributes, including the highest acorn weight (2.82 g) and moisture content (64.88%). The variation in seed traits suggests a strong influence of altitudinal and environmental gradients on seed development, which could have significant implications for seedling vigor, natural regeneration, and conservation strategies. This study provides valuable insights into seed quality parameters useful for selecting optimal seed sources for afforestation and restoration programs in Himalayan ecosystems.

Keywords: *Quercus leucotrichophora*, Seed traits, Provenance, Elevation, Seed size, Ban oak

The genus *Quercus* includes more than 400 species, and *Quercus leucotrichohora* A. Camus (Ban Oak) is one of the most important tree species in temperate and subtropical plant communities. *Q. leucotrichophora* is the commonest oak of the Western Himalayas, extending eastward to Nepal, within an altitude range from 1000 to 2400 m asl (above sea level) but occasionally descending lower in moist situations (Saklani et al., 2012). Ban oak is a dominant broadleaved species in the mid-elevation zones of the Western Himalayas, and is a major forest-forming tree species in Himachal Pradesh, playing a crucial role in maintaining ecological stability, supporting biodiversity, and sustaining rural livelihoods through fodder, fuelwood, and soil conservation functions (Barman et al., 2023). It is challenging for the species to regenerate because of the ongoing anthropogenic disturbances, such as lopping, which alter stand structure and species composition in oak forests (Amare and Bhardwaj 2016), coupled with climate variability, both of which have negatively impacted its natural regeneration capacity (Bhatt and Ram 2015). The ban oak forest is a crucial part of the Himalayan ecosystem from the perspective of biodiversity preservation and locals typically associate oaks with water and soil conservation and the maintenance of rural livelihoods (Tamta 2016). Due to its numerous uses as fodder, fuel wood, tiny lumber, and charcoal, the species is under significant biotic pressure. Its regeneration is very poor, partly due to over-exploitation and partly due to damage to seed populations by the insect (*Calandra sculpturata*) and the Himalayan langoor (*Presbytis entellus*). Mast seed year in *Q. leucotrichophora* takes place in intervals of every 2-3 years, which may be another reason for its poor regeneration.

The ripening of seeds plays a significant role in the life cycle of forest trees. Earlier studies have shown that seed traits vary considerably across geographical and altitudinal gradients, reflecting local adaptations and environmental influences (Pandit et al., 2002, Bhuva et al., 2024). In Himalayan oak species, these variations are often linked with seed maturation timing, nutrient allocation, and microclimatic factors, which ultimately govern regeneration patterns (Bhatt and Ram 2015). Among the key factors influencing regeneration potential, seed characteristics such as size, weight, and moisture content are considered critical determinants of seed viability, germination success, and seedling vigor (Tewari et al., 2019, Chauhan et al., 2021, Fox et al., 1994, Joshi et al., 2022). Khera (2010) observed that variations in seed maturation times reflect climatic influences on forest tree species, affecting stand structure, regeneration, and development; thus, identifying precise seed maturation periods is essential for effective seed collection and regeneration (Murali and Sukumar 1994). However, limited comprehensive studies have been conducted to quantify such variations in *Q. leucotrichophora* across diverse provenances in Himachal Pradesh.

Establishment of plantations of this native multipurpose tree species is recommended as a suitable conservation strategy. In this Himalayan region, the lack of quality planting material could be improved by selecting a more suitable provenance. Therefore, this study aimed to assess provenance-wise variation in key seed traits of *Q. leucotrichophora* to identify potential seed sources with superior physiological attributes, thereby contributing to more effective conservation and afforestation strategies in the region.

MATERIAL AND METHODS

Seed collection: Seeds were collected from 15 provenances of Himachal Pradesh, including Banikhet, Bharmour, Banjor, Manali, Palampur, Dharamshala, Shoghi, Rampur, Haripurdhar, Sarahan, Kandaghat, Rajgarh, Oachghat, Joginder Nagar, and Rewalsar, which provided fully grown acorns of *Q. leucotrichophora* (Fig. 1). The study sites were located between 30°58'-32°24´ N Latitude and 75°94´-77°63 E Longitude along an elevational transect of 1220 to 2206 m in Himachal Pradesh, India. At each provenance, five mature *Q. leucotrichophora* trees that were phenotypically superior and had a well-developed crown were chosen at random and marked for seed collection (Table 1). Using measuring tapes and a Ravi multimeter, the height and DBH (1.37 m) of each chosen tree were calculated. Each tree was 100 m apart from the other to avoid narrowing down the variation sampled due to relatedness (Schmidt 2000). From the first week of October to the last week of December, the collection of *Q. leucotrichophora* acorns (with involucre) began at all provenances. From each provenance bulk seed sample was collected and brought to the laboratory, and allowed to dry in shade for 24 h. The sample collected from each provenance was then placed in a cotton bag, allotted an accession number, and a name of place, and stored in a cooling incubator for further experiments.

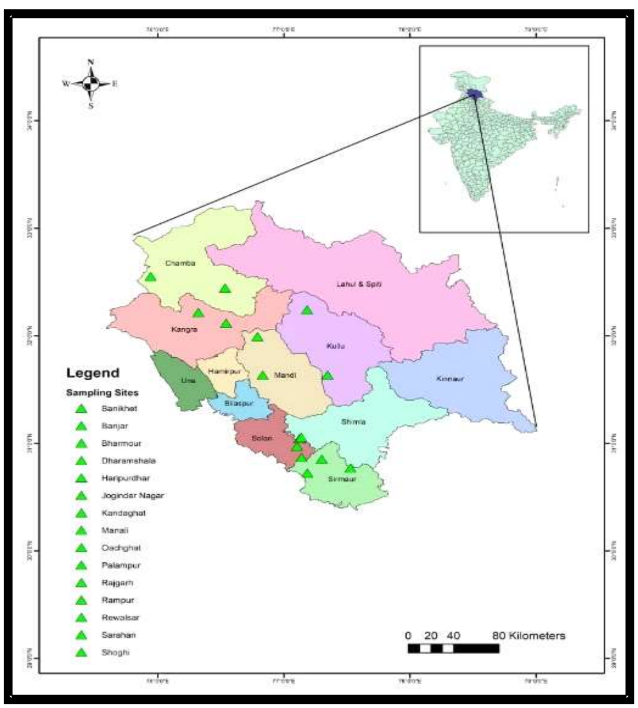

Fig. 1. Map of the study area

Acorns were visually classified as small, medium, and large-sized, and seed length, seed width were measured by using a digital vernier calliper, whereas seed weight was measured by using a digital electronic balance. To identify the seed properties, the involucre (outer seed-based cap) was removed. To create a composite seed sample, the seeds were gathered from the chosen trees at each provenance. The seed lot's five replicated batches of 25 seeds each were utilised to calculate various seed properties.

Seed morphology: The moisture percentage of each seed sample was determined on a fresh weight basis by drying the seeds at 103 ± 2°C as per ISTA (1999) rules (Table 2). Seed length and breadth (in the middle portion of the seed) were measured (using a digital vernier calliper) on five replicate samples, each consisting of 100 seeds randomly drawn from each seed lot. Seed weight (g/100 seed) was recorded by choosing eight random samples of each population, *i.e.*, 100 seeds per seed lot (ISTA 1999). Five samples (each of 100 seeds) were drawn from the seed lot of each provenance, and the number of seeds damaged due to insect attack and healthy seeds was separated. Number of seeds per 100 g were calculated (Tewari et al., 2017).

Seed biochemical parameters: The freshly harvested acorns were washed with distilled water, and the excess water was absorbed by keeping the seeds between the folds of blotting paper. After that, the seeds were dried for 24 hours in an oven at 70℃. The dried seeds were crushed to a coarse powder using metallic mortar and pestle to estimate various biochemical parameters. The total sugar, starch, total phenols, and soluble proteins in the seeds were estimated with respect to the dry weight of the seeds (Bewley and Black 1994, Mahadevan and Shridhar 1982).

Statistical analysis: Descriptive statistics was made directly from a spreadsheet in Windows Excel 2017. Analysis of variance was assessed by using the Statistical Package for Social Sciences (SPSS) version 20.0 software.

RESULTS AND DISCUSSION

Acorn physical and biochemical characters: To understand how different provenances and seed sizes influence the *Q. leucotrichophora* seed morphological traits, various physical traits (such as acorn length, width, moisture content, and 100-seed weight) and biochemical properties (including total sugar, phenol, starch, and soluble protein content) were carefully studied.

Acorn length (cm): Significant variations in *Q. leucotrichophora* acorn length among provenances and seed sizes reflected inherent genetic diversity and environmental influences (Table 3). Provenance P_9 (Haripurdhar) recorded the maximum acorn length (2.28 cm), consistent with observations that higher altitudes can enhance seed morphological attributes due to adaptive selection (Ginwal et al., 2005). The significantly greater acorn length in larger seeds (S_3: 2.37 cm) supports previous findings that seed size is positively correlated with embryo development and reserve accumulation (Deb and Sundriyal 2017). The non-significant P × S interaction suggests consistent size trends across geographic regions.

Acorn width (cm): The provenance and seed size significantly influenced the acorn width of *Q. leucotrichophora* (Table 4). The acorn width followed a similar pattern, with larger seed size classes (S_3: 1.28 cm) displaying significantly greater width, likely due to enhanced pericarp development and nutrient accumulation. Haripurdhar and Sarahan provenances displayed superior width, suggesting eco-geographical influence, especially under cooler climates and fertile soils (Rawat et al., 2022). The uniform increase in width with seed size across provenances implies a strong genetic control over radial seed traits. The study highlight the importance of selecting both suitable provenances and larger seed sizes to enhance initial seedling traits, which is often linked to seed vigor and subsequent nursery performance.

Acorn moisture content (%): The significant influence of provenance and seed size on *Quercus leucotrichophora* acorn moisture content was observed (Table 5). Larger seeds exhibited higher moisture retention (S_3: 64.88%), aligning with the hypothesis that bigger seeds contain more hydrophilic storage tissues (Harrington and Kozlowski 1972). Provenance P_9 again led with the highest mean moisture, reinforcing its potential for superior seed physiology. Differences in microclimate, especially relative humidity and soil moisture regimes, likely contributed to these variations. This indicates a direct positive correlation between seed size and moisture content, likely due to the greater volume and capacity of larger seeds to retain water. However, the interaction between provenance and seed size was non-significant, suggesting that the trend of increasing moisture content with seed size was consistent across different geographic origins. These findings underscore the importance of selecting not only optimal seed sizes but also superior provenances for maximizing seed moisture content- an essential parameter for seed vigor, storage viability, and germination performance in nursery practices.

Table 2. Seed size categories

Seed grade	Seed category	Average acorn weight (g)
S_1	Small	1.78
S_2	Medium	2.56
S_3	Large	2.82

Table 1. Geographical origin of *Q. leucotrichophora* seed sampling locations and soil pH value

Provenance	Districts	Code	Elevation (m amsl)	Latitude (°N)	Longitude (°E)	Rainfall (mm)	Soil pH
Banikhet	Chamba	P_1	1700	32° 55′	75° 94′	1600 mm	6.0
Bharmour	Chamba	P_2	2133	32° 44′	76° 53′	1550 mm	5.6
Banjar	Kullu	P_3	1356	31° 63′	77° 34′	1360 mm	6.3
Manali	Kullu	P_4	2050	32° 24′	77° 19′	1363 mm	6.0
Palampur	Kangra	P_5	1300	32° 11′	76° 53′	1750 mm	6.2
Dharamshala	Kangra	P_6	1457	32° 22′	76° 32′	1800 mm	6.0
Shoghi	Shimla	P_7	1712	31° 04′	77° 12′	1520 mm	6.0
Rampur	Shimla	P_8	1675	31° 45′	77° 63′	1480 mm	5.8
Haripurdhar	Sirmaur	P_9	2206	30° 77′	77° 53′	1420 mm	5.5
Sarahan	Sirmaur	P_{10}	1668	30° 73′	77° 19′	1500 mm	5.8
Rajgarh	Sirmaur	P_{11}	1586	30° 58′	77° 30′	1400 mm	6.0
Oachghat	Solan	P_{12}	1472	30° 87′	77° 14′	1380 mm	6.1
Kandaghat	Solan	P_{13}	1425	30° 97′	77° 11′	1350 mm	6.0
Joginder Nagar	Mandi	P_{14}	1220	31° 99′	76° 79′	1850 mm	6.3
Rewalsar	Mandi	P_{15}	1360	31° 63′	76° 83′	1820 mm	6.2

100 Seed weight (g): Both provenance and seed size significantly influenced the 100 seed weight of *Q. leucotrichophora* acorns. Seed weight is a direct measure of seed vigor and resource availability (Table 6). A progressive increase in 100-seed weight from S_1 to S_3 reflects the metabolic advantage of larger seeds in developing heavier cotyledons (Moles and Westoby 2006). Haripurdhar provenance (P_9) again emerged as the best performer

Table 3. Effect of provenances, seed size, and their interaction on acorn length (cm)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	1.95	2.12	2.29	2.12
P_2 (Bharmour)	1.98	2.13	2.3	2.14
P_3 (Banjar)	1.99	2.14	2.3	2.14
P_4 (Manali)	2.0	2.14	2.3	2.15
P_5 (Palampur)	2.0	2.15	2.33	2.16
P_6 (Dharamshala)	2.0	2.15	2.34	2.16
P_7 (Shoghi)	2.05	2.23	2.47	2.25
P_8 (Rampur)	2.04	2.23	2.42	2.23
P_9 (Haripurdhar)	2.08	2.26	2.52	2.28
P_{10} (Sarahan)	2.07	2.25	2.48	2.27
P_{11} (Rajgarh)	2.06	2.23	2.44	2.24
P_{12} (Oachghat)	2.03	2.21	2.36	2.20
P_{13} (Kandaghat)	2.03	2.21	2.4	2.21
P_{14} (Joginder Nagar)	1.89	2.09	2.27	2.09
P_{15} (Rewalsar)	1.95	2.1	2.28	2.11
Mean	2.01	2.18	2.37	

CD (p-0.05) :P =0.07 , S = 0.03, P × S =N.S.

Table 4. Effect of provenances, seed size, and their interaction on acorn width (cm)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	0.99	1.09	1.24	1.11
P_2 (Bharmour)	0.99	1.10	1.25	1.11
P_3 (Banjar)	1.00	1.13	1.26	1.13
P_4 (Manali)	1.00	1.13	1.27	1.14
P_5 (Palampur)	1.00	1.15	1.27	1.14
P_6 (Dharamshala)	1.01	1.15	1.28	1.15
P_7 (Shoghi)	1.05	1.19	1.31	1.18
P_8 (Rampur)	1.03	1.17	1.3	1.16
P_9 (Haripurdhar)	1.07	1.21	1.37	1.21
P_{10} (Sarahan)	1.06	1.21	1.35	1.21
P_{11} (Rajgarh)	1.05	1.20	1.33	1.19
P_{12} (Oachghat)	1.02	1.15	1.29	1.15
P_{13} (Kandaghat)	1.03	1.17	1.30	1.17
P_{14} (Joginder Nagar)	0.95	1.07	1.22	1.08
P_{15} (Rewalsar)	0.96	1.07	1.23	1.09
Mean	1.01	1.15	1.28	

CD (p-0.05) :P =0.03 , S = 0.01, P × S =N.S.

(242.25 g), consistent with reports that higher altitude provenances often produce denser seeds due to prolonged developmental periods and adaptive nutrient allocation (Tewari et al., 2019). This suggests that selecting large seeds from superior provenances could be a viable strategy for nursery propagation and reforestation programs aimed at enhancing early seedling performance.

Total sugar (%): The total sugar content of *Q.*

Table 5. Effect of provenances, seed size, and their interaction on acorn moisture content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	58.09	60.32	63.6	60.67
P_2 (Bharmour)	56.59	60.35	63.73	60.22
P_3 (Banjar)	56.52	60.61	64.07	60.4
P_4 (Manali)	58.32	60.6	64.39	61.11
P_5 (Palampur)	58.38	60.66	64.48	61.18
P_6 (Dharamshala)	58.74	60.88	64.56	61.39
P_7 (Shoghi)	59.5	62.25	65.66	62.47
P_8 (Rampur)	59.5	61.72	65.63	62.28
P_9 (Haripurdhar)	59.61	63.1	68.92	63.87
P_{10} (Sarahan)	59.6	62.58	66.16	62.78
P_{11} (Rajgarh)	59.57	62.39	65.57	62.51
P_{12} (Oachghat)	59.1	61.3	64.67	61.69
P_{13} (Kandaghat)	59.31	61.39	64.86	61.85
P_{14} (Joginder Nagar)	56.6	59.76	63.33	59.89
P_{15} (Rewalsar)	57.51	60.14	63.53	60.39
Mean	58.46	61.2	64.88	

CD (p=0.05)- P-2.20, S -0.10, P × S - N.S.

Table 6. Effect of provenances, seed size, and interaction on acorn 100 seed weight (g)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	174.51	244.94	281.45	233.64
P_2 (Bharmour)	175.21	245.90	280.59	233.90
P_3 (Banjar)	178.66	242.72	278.87	233.42
P_4 (Manali)	176.20	243.00	280.56	233.25
P_5 (Palampur)	183.26	246.41	283.74	237.71
P_6 (Dharamshala)	177.13	245.86	281.37	234.79
P_7 (Shoghi)	182.36	247.85	280.40	236.87
P_8 (Rampur)	178.66	247.35	283.66	236.56
P_9 (Haripurdhar)	186.32	248.48	291.47	242.25
P_{10} (Sarahan)	177.06	248.10	283.04	239.06
P_{11} (Rajgarh)	186.57	247.88	282.76	239.07
P_{12} (Oachghat)	177.80	248.91	283.46	236.72
P_{13} (Kandaghat)	179.18	244.18	283.89	235.75
P_{14} (Joginder Nagar)	172.03	243.91	278.66	231.54
P_{15} (Rewalsar)	175.51	250.53	278.70	234.91
Mean	178.70	246.43	282.16	

CD (p=0.05)- P - 4.0, -S - 1.80. P × S -N.S.

leucotrichophora acorns varied across different provenances and seed sizes, though the differences were statistically non-significant (Table 7). Although not statistically significant, trends in total sugar content showed that larger seeds (S_3: 1.63%) and certain provenances (e.g., P_9: 1.68%) tend to accumulate more carbohydrates. This aligns with previous observations that high sugar levels in seeds enhance early metabolic activity during germination. While provenance

Table 7. Effect of provenances, seed size, and their interaction on acorn total sugar content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	1.53	1.56	1.58	1.56
P_2 (Bharmour)	1.55	1.57	1.59	1.57
P_3 (Banjar)	1.57	1.59	1.6	1.59
P_4 (Manali)	1.55	1.59	1.6	1.58
P_5 (Palampur)	1.56	1.62	1.61	1.6
P_6 (Dharamshala)	1.56	1.63	1.62	1.6
P_7 (Shoghi)	1.6	1.64	1.65	1.63
P_8 (Rampur)	1.59	1.64	1.65	1.63
P_9 (Haripurdhar)	1.66	1.67	1.69	1.68
P_{10} (Sarahan)	1.65	1.66	1.68	1.67
P_{11} (Rajgarh)	1.62	1.64	1.66	1.64
P_{12} (Oachghat)	1.58	1.63	1.64	1.61
P_{13} (Kandaghat)	1.58	1.63	1.64	1.62
P_{14} (Joginder Nagar)	1.51	1.54	1.57	1.54
P_{15} (Rewalsar)	1.52	1.55	1.58	1.55
Mean	1.58	1.61	1.63	

CD (p=0.05)-P -NS , S = NS , P × S - NS

Table 8. Effect of provenances, seed size, and their interaction on acorn total phenol content (mg/g)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	39.7	41.26	44.97	41.98
P_2 (Bharmour)	39.11	42.64	44.68	42.14
P_3 (Banjar)	39.24	42.99	45.53	42.59
P_4 (Manali)	39.78	43.36	45.86	43.0
P_5 (Palampur)	42.12	42.88	46.15	43.72
P_6 (Dharamshala)	41.24	43.98	47.06	44.09
P_7 (Shoghi)	45.08	46.82	49.06	46.99
P_8 (Rampur)	43.88	46.62	48.46	46.32
P_9 (Haripurdhar)	45.97	49.26	50.69	48.64
P_{10} (Sarahan)	45.44	48.37	49.61	47.81
P_{11} (Rajgarh)	45.31	47.91	49.51	47.58
P_{12} (Oachghat)	42.0	44.71	47.17	44.62
P_{13} (Kandaghat)	43.16	45.57	47.71	45.48
P_{14} (Joginder Nagar)	38.23	40.38	43.5	40.7
P_{15} (Rewalsar)	38.45	40.7	44.11	41.08
Mean	41.91	44.5	46.94	

CD (p=0.05) P -NS, S -2.66, P × S- NS.

influence was subtle, environmental cues like light and canopy exposure could modulate carbohydrate biosynthesis in developing acorns, which may have implications for seedling vigor and nursery performance.

Total phenol (mg/g): The total phenol content in *Q. leucotrichophora* acorns showed considerable variation across different provenances and seed sizes (Table 8). Phenolic compounds serve as biochemical defence markers

Table 9. Effect of provenances, seed size, and their interaction on a corn starch content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	48.76	49.6	51.83	50.06
P_2 (Bharmour)	48.53	50.0	52.17	50.23
P_3 (Banjar)	48.71	50.5	53.17	50.79
P_4 (Manali)	48.74	50.65	53.34	50.91
P_5 (Palampur)	48.59	50.67	53.47	50.91
P_6 (Dharamshala)	49.62	50.76	53.57	51.31
P_7 (Shoghi)	51.15	53.18	55.4	53.24
P_8 (Rampur)	50.07	52.81	55.03	52.64
P_9 (Haripurdhar)	51.44	54.23	57.68	54.45
P_{10} (Sarahan)	51.32	53.45	56.48	53.75
P_{11} (Rajgarh)	51.54	53.33	55.54	53.47
P_{12} (Oachghat)	49.82	50.9	53.66	51.46
P_{13} (Kandaghat)	50.09	50.95	54.03	51.69
P_{14} (Joginder Nagar)	47.1	48.63	50.93	48.89
P_{15} (Rewalsar)	48.06	48.73	50.97	49.25
Mean	49.57	51.23	53.82	

CD (p-0.05) - P- 2.57, S -2.15. P × S - NS.

Table 10. Effect of provenances, seed size, and their interaction on acorn soluble protein content (%)

Provenances (P)	Seed size			Mean
	S_1	S_2	S_3	
P_1 (Banikhet)	40.83	41.12	45.66	42.54
P_2 (Bharmour)	41.52	41.62	47.42	43.52
P_3 (Banjar)	42.25	43.38	48.09	44.57
P_4 (Manali)	44.38	45.65	50.48	46.84
P_5 (Palampur)	46.23	47.56	51.43	48.41
P_6 (Dharamshala)	48.9	49.6	52.46	50.32
P_7 (Shoghi)	52.53	52.69	57.88	54.37
P_8 (Rampur)	50.54	50.57	56.95	52.68
P_9 (Haripurdhar)	57.16	58.72	60.79	58.89
P_{10} (Sarahan)	55.39	56.93	59.68	57.34
P_{11} (Rajgarh)	53.56	54.69	58.74	55.66
P_{12} (Oachghat)	51.34	51.43	54.69	52.49
P_{13} (Kandaghat)	51.83	51.9	55.78	53.17
P_{14} (Joginder Nagar)	39.53	39.57	45.0	41.37
P_{15} (Rewalsar)	39.61	39.89	45.3	41.6
Mean	47.71	48.36	52.69	

CD (p-0.05) - P -1.24 , S- 0.56, P × S -NS.

and antioxidant agents. Seed size significantly influenced total phenol concentration, with S_3 recording the highest (46.94 mg/g), implying a higher investment in protective secondary metabolites. Although not statistically significant, the consistent superiority of P_9, P_{10}, and P_{11} suggests a localized selection for phenolic richness under biotic stress or high UV conditions (Sytar and Hajihashemi 2024).

Starch (%): The acorn starch content (%), a primary energy reserve for germination, was significantly influenced by provenance and seed size, whereas the interaction between provenance and seed size was non-significant (Table 9). S_3 acorns showed the highest starch concentration (53.82%), supporting literature linking large seeds with enhanced energy reserves (Leishman et al., 2000). The high-starch provenances (Haripurdhar and Sarahan) may thus be considered for nursery use in low-input environments where endogenous reserves are critical for establishment.

Soluble protein (%): Both provenance and seed size have a significant influence on the soluble protein content of acorns (Table 10). Soluble protein content was highest in large seeds (S_3: 52.69%) and in provenances like Haripurdhar (58.89%), suggesting that both genetic and size-based factors contribute to storage protein accumulation. Proteins in seeds play a vital role in enzyme function and nitrogen availability during seedling establishment (Shewry and Halford 2002). The observed pattern suggests selection of large-seeded genotypes from superior provenances could be an effective strategy to enhance soluble protein content in acorns and thus enhance early growth potential.

CONCLUSION

The present study highlighted significant variation in the physical and biochemical characteristics of *Q. leucotrichophora* acorns as influenced by seed size and provenance. Larger seeds consistently exhibited superior values for key parameters such as acorn length, width, moisture content, and 100-seed weight, indicating their potential for better germination and seedling vigor. Biochemical analyses revealed that larger seeds also contained higher concentrations of total sugars, phenolics, starch, and soluble proteins, underscoring their enhanced nutritional and physiological quality. Provenance-level comparisons demonstrated that local environmental factors substantially influence trait expression, reaffirming the role of genotype × environment interactions. These findings provide a vital basis for selecting superior seed sources and seed sizes for conservation, afforestation, and nursery management practices aimed at improving forest productivity and regeneration success in Himalayan oak ecosystems.

AUTHOR's CONTRIBUTION

Jayashree Behera: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing-original draft, Writing-review & editing. CL Thakur: Conceptualization, Investigation, Supervision, Validation. DR Bhardwaj: Formal analysis, Methodology, Resources, Supervision. Saurabh Sharma: Data curation, Visualization, Writing-review & editing.

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