

Evaluating genetic variation in growth, needles, wood and oleoresin traits among various half-sib families of *Pinus roxburghii*

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Abstract

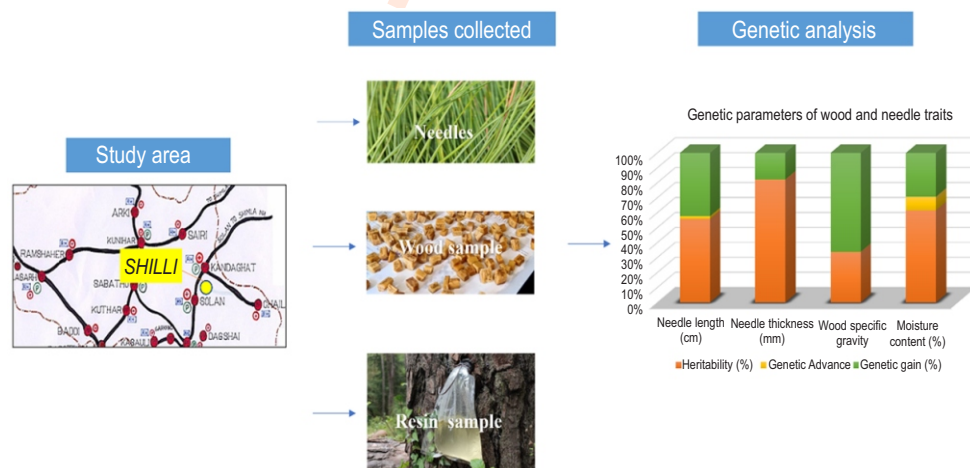
Aim: This study examines genetic variability in growth, needle, wood, and oleoresin traits of high-resin-yielding *Pinus roxburghii* (Sargent) families in the Shilli conservation reserve, Solan, Himachal Pradesh, India. The research investigates how these genetic traits correlate with resin yield and evaluates their heritability to enhance breeding and forestry programs.

Methodology: Fieldwork was conducted in a Chir pine block plantation, measuring traits like DBH, needle thickness, wood specific gravity, and oleoresin yield. Genetic analysis involved heritability estimates, genetic gain calculations, and principal component analysis to assess trait correlations and diversity.

Results: Needle thickness showed the highest heritability (97%), while moisture content had the most significant genetic advance (7.18%). Notably, resin yield displayed a positive correlation with diameter at breast height (0.737), moisture content (0.672) and wood specific gravity (0.616), indicating potential indirect selection targets in breeding.

Interpretation: The study identifies influential genetic traits in enhancing resin yield and wood quality in *Pinus roxburghii*. These findings suggest practical applications in selective breeding, facilitating more effective forestry management and tree development initiatives to optimize resource production.

Key words: Genetic gain, Heritability, Moisture content, Needle thickness, *Pinus roxburghii*



Introduction

Pinus roxburghii Sargent, commonly known as Chir pine or Chil, is a prominent conifer of the North-western Himalayas (Rawat et al., 2014) and belongs to Family Pinaceae, order Coniferales and form dominant evergreen forests between 1200 and 2200 m above mean sea level (Zobel et al., 1995; Manral et al., 2020). It stands out as a key species among India's six native pine species (Bhat et al., 2016). This species has immense economic value, supplying resources such as resin, timber, oleoresin and turpentine oil (Kaushik et al., 2013; Sharma et al., 2015). It is also used as fuelwood, and seeds are a source of edible oil. Various shapes of twisted wood of Chir pine are used for decoration purposes (Kala, 2004). The sites of the Chir pine are often moisture- and nutrient-deficient (Bargali and Bargali, 2000) influenced by the microclimate of the area (Joshi and Bargali, 1992; Manral et al., 2022). Notably, Chir pine is recognized by slender, needle-like leaves bundled three times, as well as dark red–brown bark with deep longitudinal fissures and scales. It is an impressively tall tree reaching up to 55 m and diameter often exceeding 100 cm (Ghildiyal et al., 2010).

The current demand necessitates careful selection and mass production of superior genotypes, underscoring the importance of evaluating wood traits (Singh et al., 2009). Chir pine is the main commercially utilised species for oleoresin in India. Oleoresin production plays a crucial role in sectors that rely on it and provides work opportunities for many rural residents. Mature pine trees are essential for successful oleoresin tapping and its associated businesses (Sharma and Lekha, 2013). The considerable variability in pine resin productivity across different environmental conditions suggests the potential for substantial enhancement. Among Indian states, Himachal Pradesh has emerged as the state for Chir pine cultivation and development. Hence, preservation and effective management of this species' genetic resources are highly important (Sharma et al., 2002).

Genetic diversity of a species is pivotal for its adaptability and resistance to environmental stress and change (Potter et al., 2017), helping populations to adapt and evolve over time (Gul et al., 2021). Chir pine, critical to the Western Himalayas' ecosystem and economy, requires genetic diversity to boost production and tolerance to a variety of environmental conditions. Conserving genetic diversity not only assures the availability of superior genotypes for propagation, but it also improves the general health of forests. Plants adapt to their changing environment via modifying their morpho-physiological, bio-chemical, phenological and behavior traits (Nock et al., 2016; Khatri et al., 2023a). Plant behavior are plastic responses to environmental conditions (Karban, 2015) and plants respond to their environment with ample flexibility via producing variable characteristics which benefit the plant performance with varying climatic conditions (Negi et al., 2024). The property of a genotype to show fluctuations in trait values under different environmental conditions is known as phenotypic plasticity (Nicotra et al., 2015; Khatri et al., 2023b), which alter the interaction between

organisms and the biotic and abiotic factors of its environment (Miner et al., 2005; Khatri et al., 2022). Himachal Pradesh comprises of vast landscapes with large variation in climate, soil topography, which leads to substantial variance in the population of plant species stretching across the state. In light of these factors, the assessment of oleoresin, wood and needle traits at regional level are important for identifying genotypes with improved wood quality and assisting in the formulation of advanced breeding strategies (Frampton, 1996). Genetic evaluation of needle and wood traits in Chir pine will identify superior genotypes for improved productivity, wood quality, and climate change mitigation. Hence, the present study focused on an in-depth examination of heritability and other genetic attributes associated with growth, wood, needle and oleoresin traits of different half sib families of *P. roxburghii* Sargent. This study would be helpful to the silviculturists, and planners as well as ecologists to select the species of choice to get the quality material and other ecosystem goods and services.

Materials and Methods

The present study was carried out at Shilli Conservation Reserve, Solan, during the year 2020-2021, where a block plantation of high resin-yielding trees, selected from 19 provenances of Himachal Pradesh selected on the basis of oleoresin properties, was established in 1982 (Table 1). The study area experience a subtropical climate with temperatures ranging from -4°C in winter to 32°C in summer and an average annual rainfall of 1250 mm. The soils are somewhat sandy to loamy texture due to weathering of quartzite and schist parent rocks. The half-sib families from the plantation were evaluated for various growth traits, needle characteristics and wood traits, followed by their oleo resin yield and quality examination.

The block plantation comprised of 190 trees (10 trees of 19 high resin yielding half-sib families each). Among the 190 trees, 95 were evaluated in the field trials, i.e., 5 genotypes from each family were used to study within-family and between-family variation. The statistical design was employed in a randomized block design (RBD). Needle characteristics (Table 2), such as needle length (NL) and needle thickness (NT), were measured by scale and Vernier caliper, and the number of stomata (NS) were calculated by method of Johansen (1940), whereas growth traits were assessed by standard methods, such as the Ravi multimeter for tree height (H) in meters, tree caliper, to measure the diameter at breast height (DBH) (1.37 m) in centimeters, Swedish bark gauge to measure the bark thickness (BT) in millimeters, and Ravi altimeter to measure the crown length (CL) and crown height (CH) in meters (Chatturvedi and Khanna, 2011). Wood characteristics such as moisture content (MC) were determined by measuring the difference between the fresh weight and oven-dried weight of the samples.

The wood specific gravity (WSG) was calculated by comparing the weight of a given volume of wood with the weight of an equivalent volume of water. Tracheid length (TL) was

Table 1: Details of 19 half-sib families of Chir pine used in this study

Family	Provenance	Districts	Altitude	Latitude	Longitude
T ₁	Mahasu	Shimla	1700	31.111	77.502
T ₂	Chanina	Kangra	480	32.207	75.767
T ₃	Soigni	Mandi	860	31.709	76.925
T ₄	Surami	Bilaspur	590	31.410	76.674
T ₅	Jassi	Kangra	650	31.995	76.266
T ₆	Bitroli	Hamirpur	660	31.847	76.487
T ₇	Surami	Bilaspur	600	31.406	76.673
T ₈	Bijhri	Hamirpur	850	31.524	76.533
T ₉	Majhin	Kangra	930	31.825	76.391
T ₁₀	Hamirpur	Hamirpur	750	31.694	76.515
T ₁₁	Hamirpur	Hamirpur	720	31.690	76.503
T ₁₂	Dharamshala	Kangra	1560	32.228	76.321
T ₁₃	Bijhri	Hamirpur	870	31.521	76.538
T ₁₄	Hamirpur	Hamirpur	830	31.699	76.510
T ₁₅	Majhin	Kangra	790	31.821	76.394
T ₁₆	Chabhitra	Kangra	540	32.026	76.116
T ₁₇	Bharwain	Una	920	31.799	76.127
T ₁₈	Mahasu	Shimla	1650	31.111	77.501
T ₁₉	Habroi	Kangra	960	32.082	76.455

Table 2: Variation in the mean performance of needle and wood traits among different half-sib families of Chir pine

Family	Needle length (cm)	Needle thickness (mm)	No. of stomata/mm	Wood specific gravity (g cm ⁻³)	Tracheid length (mm)	Moisture content (%)
T ₁	25.89	0.73	10.07	0.41	1.64	66.25
T ₂	28.00	0.74	9.97	0.42	1.63	71.74
T ₃	26.40	0.68	9.56	0.41	1.63	62.01
T ₄	26.04	0.71	9.33	0.42	1.68	59.85
T ₅	25.79	0.72	9.79	0.42	1.66	59.20
T ₆	26.43	0.72	9.97	0.42	1.68	62.98
T ₇	25.93	0.68	10.07	0.43	1.56	72.03
T ₈	25.73	0.68	9.53	0.40	1.69	64.30
T ₉	26.10	0.69	9.24	0.43	1.68	66.35
T ₁₀	25.87	0.71	9.66	0.42	1.70	60.32
T ₁₁	27.04	0.64	9.29	0.44	1.68	62.48
T ₁₂	24.87	0.70	9.41	0.41	1.64	59.10
T ₁₃	25.83	0.72	9.97	0.44	1.68	68.54
T ₁₄	26.10	0.69	10.42	0.45	1.59	79.79
T ₁₅	20.83	0.67	8.08	0.42	1.65	63.81
T ₁₆	23.47	0.64	7.85	0.41	1.70	60.46
T ₁₇	25.67	0.73	9.41	0.43	1.65	67.05
T ₁₈	24.30	0.63	9.30	0.42	1.67	55.67
T ₁₉	25.33	0.71	10.15	0.43	1.73	65.55
Mean	25.57	0.70	9.53	0.42	1.66	64.60
C.D. 0.05	1.12	0.03	0.47	0.02	0.05	2.87
C.V.	2.64	2.51	2.94	2.09	1.92	2.67

assessed by the method outlined by Pandey *et al.* (1968), with the average length obtained from 25 tracheids. Oleoresin collected by bore hole technique, was analyzed for its color, turpentine content (TC) and rosin content (RC) (Kumar *et al.*, 2022).

Statistical analysis: The statistical design employed was a Randomized Block Design (RBD), and analysis of variance (ANOVA) was conducted using the General Linear Model (GLM) procedure in SPSS version 16. Graphical representations were generated using the statistical software RStudio (Posit Team,

2023). Genetic parameters, including phenotypic variance (Vp), genotypic variance (Vg), and environmental variance (Ve), were computed by the formula given by Singh and Chaudhary (1985). To assess trait variability, the phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) were calculated following the method of Burton and DeVane's (1953). Broad-sense heritability (H²), genetic advance (GA) and genetic gain (GG) were evaluated as per guidelines of Johnson et al. (1955). Principal component analysis, also known as canonical vector analysis, was conducted to explore the variations across different differentiation axes, following the procedure described by Lawley and Maxwell (1962). The genotypes were statistically analysed and classified into distinct clusters using the Ward linkage method (Ward, 1963) in the SPSS software package and R software.

Results and Discussion

All Chir pine families investigated in the current study showed significant variation in the growth parameters viz., diameter at breast height, bark thickness, crown length and crown height, which is consistent with the findings of Kumar et al. (2022) who reported significant genetic variation in Chir pine growth traits, with bark thickness showing the highest heritability (80.46%), reflecting its strong genetic control, while crown length exhibited the lowest heritability (59.46%), indicating a greater environmental influence. Furthermore, diameter at breast height displayed the highest genetic advance, while bark thickness demonstrated the maximum genetic gain, highlighting its potential as a key trait for selection and improvement in Chir pine breeding programs. These variations are attributed to rapidly changing bioclimatic conditions in dissected mountainous landscapes, which result in significant heterogeneity in soil types and their chemical and physical properties (Bargali et al., 2018).

These differences provide more choices for selecting superior progeny and progeny trials that can be developed into effective seed orchards for quick genetic improvements, which is

consistent with the previous studies conducted in *P. roxburghii* forests by Meena (2023) who highlighted significant variability in *Pinus roxburghii* oleoresin yield, strongly linked to tree diameter (40–60 cm), needle traits and bark thickness. The variations in family performance may also be linked to genetic factors, as obtained in *P. sibirica* (Rui et al., 2011) and *P. mugo* (Boratynska et al., 2014). Needle characteristics, like the longest needle length (28 cm), was noted in the T₂ family, which was statistically at par with T₁₁ (27.04). Similarly, the maximum needle thickness was evident in T₂ (0.74 mm), statistically at par with T₁ (0.73) and T₁₇ (0.73). The number of stomata per mm of a row was maximum in the T₁₄ family (10.42), statistically at par with T₁₉ (10.15), T₁ (10.07), and T₁₇ (10.07) (Table 2). These results are consistent with the findings of Bhat et al. (2016) in *P. roxburghii*, who reported significant genetic variability among progenies, with needle lengths ranging from 18.10 to 24.60 cm, thickness 0.53 to 0.71 mm, and stomata density 7.33 to 12 mm⁻¹. Similarly, Yigit et al. (2016; 2023) observed substantial genetic variation in *Pinus nigra*, highlighting the influence of genetic and environmental factors on needle traits. Notably, needle length is positively correlated with oleoresin yield, making it a valuable indicator in breeding programs (Meena, 2023). Furthermore, variations in stomatal traits, such as number and density, enhance ability of pine trees to adapt water stress and elevated CO₂ levels (Zhou et al., 2013).

With respect to wood characteristics, T₁₄ presented the highest moisture content (79.79%), whereas T₁₂ presented the lowest moisture content (73.63%). These findings are consistent with those of Pang and Herritsch (2005) in *P. radiata* and Kozakiewicz et al. (2021) in Scots pine. The maximum tracheid length was found in T₁₉ (1.73 mm), which was statistically at par with families T₁₀ (1.70), T₁₆ (1.70), T₈ (1.69), T₄ (1.68), T₆ (1.68), T₉ (1.68), T₁₁ (1.68) and T₁₃ (1.68) (Table 2). Tracheid length varied with tree height for a given cambial age, with the base of the tree having the lowest number of tracheids (Megraw, 1985). Wood-specific gravity plays a vital role in wood stiffness and strength (Wright et al., 2019) and is widely recognized as an indicator of

Table 3: Estimates of variability and genetic parameters for needle and wood traits of Chir pine among different half-sib families

Traits	Needle length (cm)	Needle thickness (mm)	No. of stomata/mm	Wood specific gravity (g cm ⁻³)	Tracheid length (mm)	Moisture content (%)
Environ-mental Variance	0.45	0.02	0.08	0.07	0.01	4.84
Geno-typic Variance	2.05	0.01	0.40	0.01	0.02	46.83
Pheno-typic Variance	2.51	0.05	0.48	0.08	0.01	51.67
Geno-typic Coefficient of variation	0.33	0.10	0.19	2.91	0.20	22
Pheno-typic Coefficient of variation	0.37	0.11	0.21	9.87	0.27	23.11
Heritability (%)	81.90	97.00	84.00	9.00	57.00	91.00
Genetic advance	2.68	0.21	1.19	0.05	0.06	13.42
Genetic gain (%)	62	21	36	17.7	32	43.16

Table 4: Correlations for the needle, wood, oleoresin and growth traits among different families of Chir pine

	A	NL	NT	NS	MC	TL	WSG	RY	TC	RC	DBH	BT	H	CH
NL	-0.176	1												
NT	-0.071	0.359**	1											
NS	0.103	0.637**	0.490**	1										
MC	-0.247	0.26	0.314*	0.45**	1									
TL	-0.03	-0.08	-0.12	-0.25	-0.500**	1								
WSG	-0.186	0.191	0.001	0.288*	0.469**	-0.163	1							
RY	0.014	-0.079	-0.136	0.176	0.672**	-0.417**	0.598**	1						
TC	-0.071	0.01	-0.068	0.257	0.746**	-0.427**	0.616**	0.977**	1					
RC	0.038	-0.099	-0.163	0.144	0.641**	-0.414**	0.570**	0.995**	0.958**	1				
DBH	-0.276*	0.006	0.058	-0.024	0.700**	-0.274*	0.529**	0.737**	0.723**	0.727**	1			
BT	-0.408**	-0.039	-0.034	-0.013	0.468**	-0.159	0.434**	0.518**	0.521**	0.521**	0.652**	1		
H	0.157	-0.045	-0.034	-0.105	0.331*	-0.15	0.154	0.26	0.243	0.26	0.561**	0.175	1	
CH	-0.434**	0.249	0.131	0.204	0.622**	-0.424**	0.508**	0.587**	0.591**	0.581**	0.722**	0.553**	0.390**	1
CL	0.310*	-0.279*	-0.144	-0.249	0.133	-0.07	0.005	0.171	0.12	0.18	0.430**	0.103	0.900**	0.203

A- Altitude, NL-Needle length, NT-Needle thickness, NS-No. of stomata,MC- Moisture content,TL- Tracheid length, WSG- Wood specific gravity, RY - Resin yield, TC-Turpentine content, RC-Rosin content, DBH-Diameter at breast height, H-Height, BT-Bark thickness, CH-Crown height, CL-Crown length

Table 5: Principal component analysis for needle, wood and growth traits among different half-sib families of Chir pine

Character	Component I	Component II
NL	0.266	-0.774
NT	0.007	-0.013
NS	0.172	-0.472
MC	5.283	-1.964
TL	-0.020	0.010
WSG	0.008	0.000
DBH	4.905	1.800
BT	0.204	0.059
H	1.069	1.099
CH	0.540	0.062
CL	0.558	1.099
Eigen value	3.68	1.80
Percentage of variability (%)	76.74	14.78
Cumulative percentage of variability (%)	76.74	91.47

Principal Component Analysis on the basis of Covariance matrix

wood quality (Burdon *et al.*, 2004). The findings of the present research demonstrated the highest wood specific gravity (0.46) in T₁₄ family, which was at par with those of families T₁₁ (0.44), T₁₃ (0.44), T₇ (0.43), T₉ (0.43), T₁₇ (0.43) and T₁₉ (0.43) (Table 2), respectively, the results align with the findings of Bhat *et al.* (2016) in *P. roxburghii* who have reported significant variation in wood traits among *P. roxburghii* progenies, with moisture content ranging from 47.76 to 61.08%, tracheid length 1.51 to 1.85 mm and wood specific gravity from 0.38 to 0.46, reflecting substantial genetic diversity. Similar range of wood specific gravity was reported by Gupta *et al.* (2023) in *P. roxburghii*. Furthermore, oleoresin yield in previously published findings of Kumar *et al.* (2022), showed significant variation among families, ranging from 251 (T₅) to 780.8 g (T₁₄), with the highest yield attributed to greater

tree diameter. The genetic characteristics of these needles, wood, growth and oleoresin parameters were investigated. At phenotypic (23.11%) and genotypic level (22%), the moisture content had the largest coefficient of variance. These traits have been found to be moderately to highly heritable (Table 3). Heritability among families is often greater than individual tree heritability, as they are based on average performance from several progenies (Zobel and Talbert, 1984). Needle thickness had the highest heritability (97%), with a genetic gain of 21% whereas moisture content had the greatest genetic advance (13.42%). The maximum genetic gain was found for needle length (62%). High heritability makes it easier to identify acceptable features for selection, enabling breeders to choose superior genotypes; however, genetic evolution explains the phenotypic

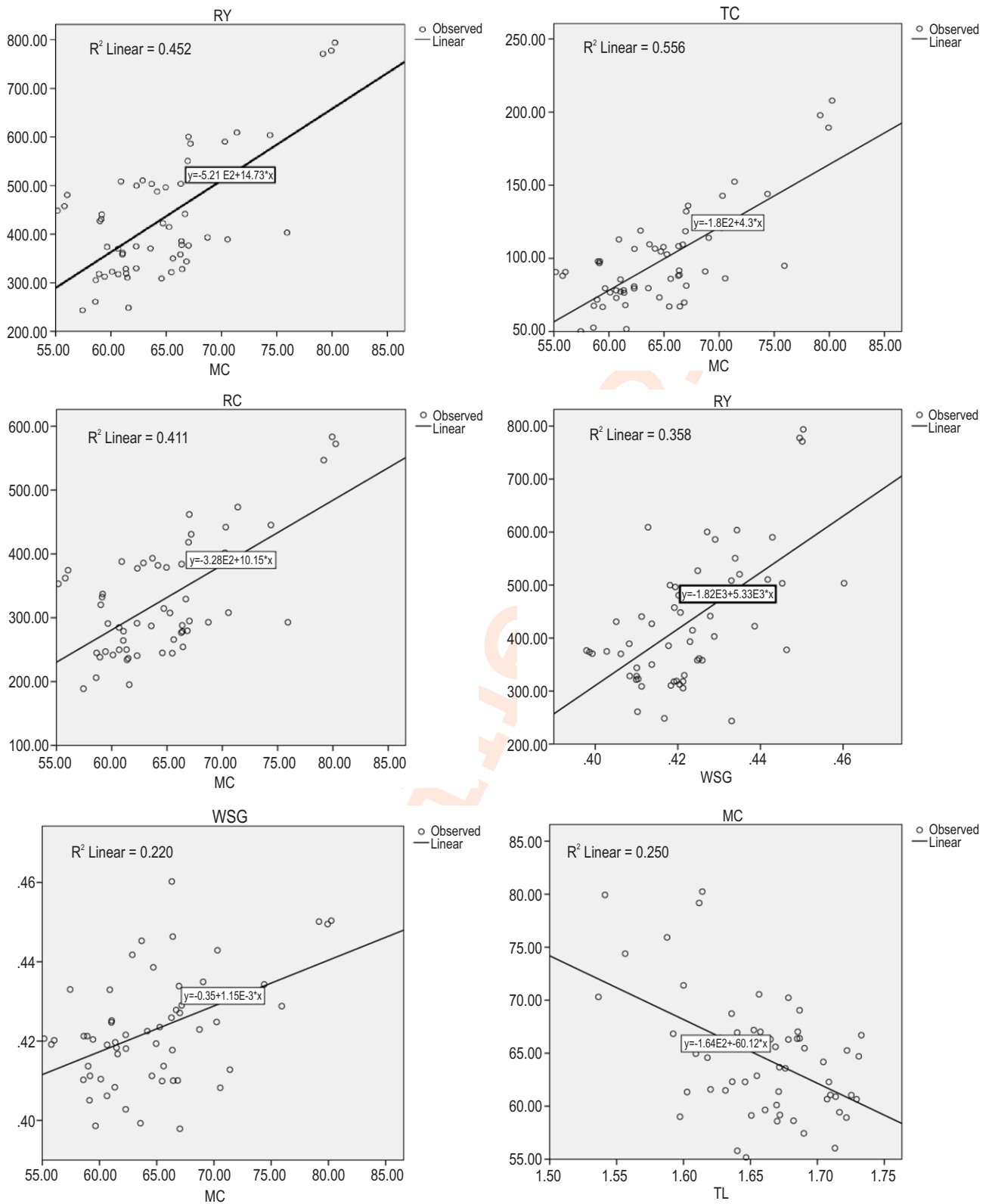


Fig. 1: Regression analysis of needle, wood, oleoresin and growth traits among different families of Chir pine. (A) Moisture content and resin yield; (B) Moisture content and turpentine content; (C) Moisture content and resin content; (D) Wood specific gravity and resin yield content; (E) Moisture content and wood specific gravity and (F) Tracheid length and moisture content.

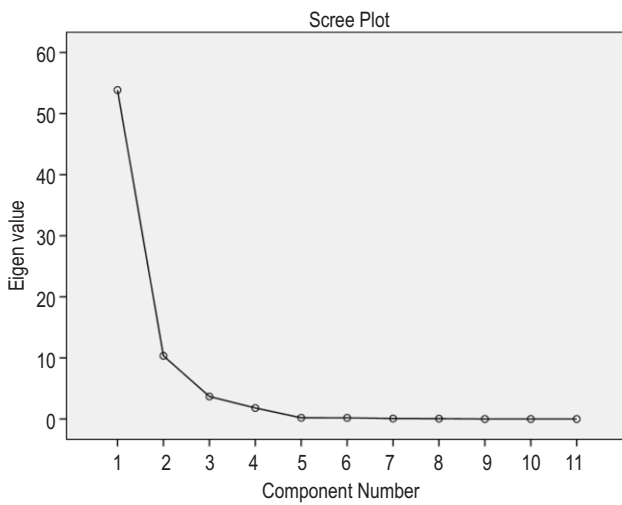


Fig. 2: Scree plot showing the eigen values of different principal components.

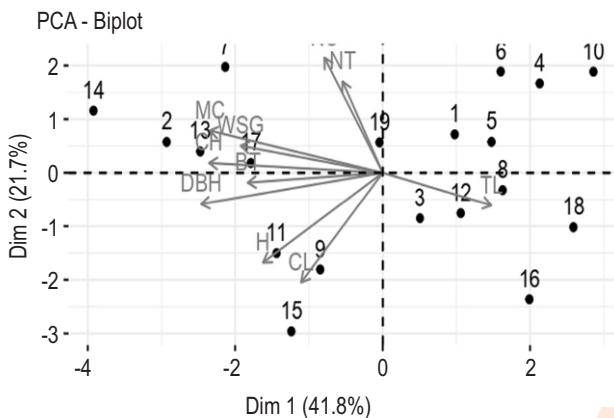


Fig. 3: PCA-Biplot of different principal components.

variability in conifer needles among ecological and geographical variances (Meng *et al.*, 2019; Dixit *et al.*, 2023).

Heritability and genetic traits emphasize the importance of variation in modern breeding programs. The strong genetic association of characteristics cause genotypic coefficient of variation to be lower than the phenotypic values (Singh *et al.*, 2013). In conifer species, genetic factors significantly influence traits such as specific gravity and tracheid length, as demonstrated by research on *P. taeda* (Dahlen *et al.*, 2023) *P. sylvestris* (Hong *et al.*, 2014) and *P. roxburghii* by (Bhat *et al.*, 2016). The specific gravity of wood showed moderate to substantial genetic gains, indicating that these traits could be valuable in enhancing the selection process for tree improvement, as noted by Isik *et al.* (2011). This trait is crucial

because it strongly affects the properties of pulp and paper products. Genetic gain estimates for various traits provide guidance for determining the method and degree of selection to be implemented in progenies. Correlation analysis is an essential method for evaluating the strength and nature of relationships between various traits, facilitating indirect selection. Since enhancing multiple traits is a primary objective in the genetic improvement of forest trees, correlation analyses provide valuable guidance for coordinated breeding strategies (Jia *et al.*, 2018). A correlation analysis of various characteristics used in the study revealed both positive and negative relationships between them (Table 4). There was a significant negative correlation between altitude and the following growth traits DBH (-0.276), BT (-0.408), CH (-0.434), and TC (-0.071) whereas the crown length (0.310) was positively correlated with altitude. In addition to needle, stomata had a strong positive correlations with NL (0.637), NT (0.490), MC (0.455) and WSG (0.288), moisture content was highly and positively correlated with DBH (0.700), RY (0.672), RC (0.641), WSG (0.469), TC (0.746), BT (0.468), and CH (0.622). Tracheid length was highly significant and negatively correlated with MC (-0.567), RY (-0.522), TC (-0.536), RC (-0.521) and CH (-0.513).

Altitude was negatively correlated with needle length, which is in line with the findings of Huang *et al.* (2016), and there was a statistically significant correlation between needle length and needle thickness. Wood specific gravity was significantly and positively correlated with RY (0.598), TC (0.616), RC (0.570), DBH (0.529), BT (0.434) and CH (0.508). Similarly, resin yield was significantly and positively correlated with TC (0.977), RC (0.995), DBH (0.737), BT (0.518), CH (0.587) and turpentine contents and with the RC (0.958), DBH (0.723), BT (0.521) and CH (0.591). RC was positively correlated with DBH (0.727), BT (0.521) and CH (0.581). DBH was positively correlated with BT (0.652) and CH (0.722) whereas tree height was positively correlated with DBH (0.561) and CL (0.900), respectively. Similar results concerning the correlations and influences between various characteristics have been reported by Lai *et al.* (2020) who proclaimed that DBH variations likely contribute to resin yield due to their influence on tree growth and resin production capacity. Joshi and Chalise (2022) also reported that variations in DBH, tracheid length and resin canal characteristics can directly affect resin yield in *P. roxburghii*.

The morphology of *P. roxburghii* needles was found to be influenced by the altitude gradient. Turpentine content was positively correlated with the oleoresin yield, suggesting that tree species exhibiting high oleoresin production also tend to have high turpentine contents. This relationship was consistently observed in studies conducted by Sukarno *et al.* (2022) in *P. merkusii*. Understanding associations at both genotypic and phenotypic levels empower breeders to devise effective breeding strategies with the aim to increase productivity. Regression analysis revealed that the moisture content was linearly related to the turpentine content ($R^2 = 0.556$), RY ($R^2 = 0.452$), rosin content ($R^2 = 0.411$) and wood specific gravity ($R^2 = 0.220$). Similarly,

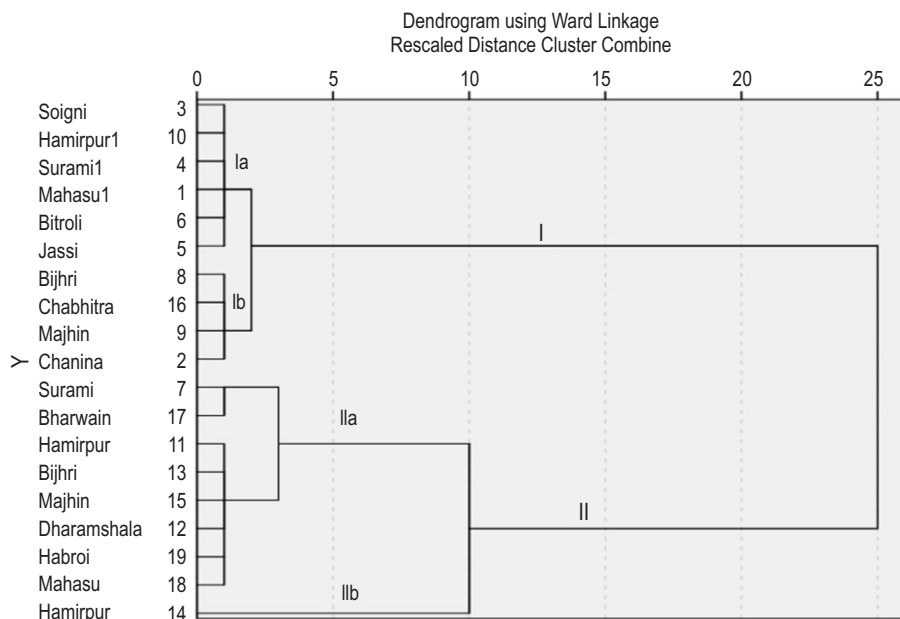


Fig. 4: Dendrogram of nineteen half-sib families of Chir pine.

tracheid length was linearly related to moisture content ($R^2 = 0.321$), and WSG to RY ($R^2 = 0.358$) (Fig. 1). The current findings corroborates Missanjo and Matsumura (2016) who perceived significant linear relationships between moisture content, turpentine content, rosin content and wood specific gravity. The PCA summary and factor patterns for needle, oleoresin, and wood characteristics and growth attributes are shown in Table 5. Only two components were found having eigenvalues greater than one (Fig. 2) and these components were retained for additional genetic study.

These variables accounted 91.47% variation. Component I ($\lambda_1=53.86$) explained 76.74% variation, explained by moisture content (5.28), followed by DBH (4.91) and height (1.07). Component II ($\lambda_2=10.34$) explained 14.73% of the variation, with maximum loading values of height (1.09) and crown length (1.09) (Fig. 3). The outcomes pertaining to growth traits were similar to those reported by Bhat *et al.* (2016) for *P. roxburghii* Sargent, and Huang *et al.* (2016) for *P. yunnanensis*. They also discovered that different eigenvalues (greater than one) explained varying percentages of variance for certain attributes. Nineteen half-sib families were grouped into two main clusters (Fig. 4). Clusters I and IV consisted the greatest number of families (6), including $T_3, T_{10}, T_4, T_1, T_6$ and T_5 and $T_{11}, T_{13}, T_{15}, T_{12}, T_{19}$ and T_{18} , respectively. T_{14} occurred as an outlier. Clusters I and II were closely related, being dissimilar to Clusters III and IV.

The families originated from various eco-geographical zones across the state, leading to considerable differences among them. Moreover, substantial variation in these

characteristics must be attributed to the genetic makeup of the species. As evidenced by the pattern of group constellations, geographic diversity does not necessarily correlate with genetic diversity. Similar findings have been reported earlier by Aslam *et al.* (2011) for *P. wallichiana*, Huang *et al.* (2016) for *P. yunnanensis* and Bhat *et al.* (2016) for *P. roxburghii*.

This study highlights significant genetic diversity and heritability in Chir pine, for needle thickness, needle length, and moisture content showing strong additive genetic variance on these traits that can be improved by selection. High coefficient of determination between moisture content with turpentine content ($R^2=0.556$) suggest opportunities for indirect selection in breeding programs. Key components identified through PCA emphasize traits critical for genetic improvement. The findings provide a platform for improvement in growth, wood quality, and resin production, aiding researchers and silviculturists in selecting high-oleoresin-producing trees to maximize forest productivity.

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