

**POPULATION DYNAMICS AND STAND STRUCTURE
OF *Pinus gerardiana* WALL. IN DRY TEMPERATE
FOREST OF HIMACHAL PRADESH**

Thesis

by

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(F-2021-28-D)**

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CERTIFICATE - I

This is to certify that the thesis entitled “**Population dynamics and stand structure of *Pinus gerardiana* Wall. in dry temperate forest of Himachal Pradesh**” submitted in partial fulfilment of the requirements for the award of degree of **DOCTOR OF PHILOSOPHY (FORESTRY)** in the discipline of **Forest Biology and Tree Improvement** to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, (Nauni) Solan (HP)– 173230 is a record of bonafide research work carried out by **Mr. Rajender Kumar (F-2021-28-D)** son of Shri Tapender Singh under my guidance and supervision. No part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of investigations have been fully acknowledged.

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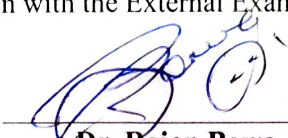
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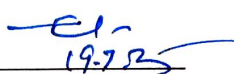
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LIST OF ABBREVIATIONS

%	:	Per cent
@	:	At the rate
°C	:	Degrees Celsius
BD	:	Bulk Density
CD	:	Critical Difference
CEC	:	Cation Exchange Capacity
cm	:	Centimeter
cm ²	:	Centimeter square
cm ³	:	Cubic centimeter
Cu	:	Copper
DBH	:	Diameter Breast Height
dSm ⁻¹	:	Deci Siemens per meter
<i>et. al</i>	:	Etalia (Coworkers)
EC	:	Electrical Conductivity
FYM	:	Farm Yard Manure
g	:	Gram
GM	:	Goat Manure
Ha	:	Hectare
ha ⁻¹	:	Per hectare
K	:	Potassium
Kg ha ⁻¹	:	Kilogram per hectare
m	:	Meter
masl	:	Mean above sea level
mm	:	Millimeter
MOT	:	Muriate of Potash
MT	:	Metric Tonnes
N	:	Nitrogen
NS	:	Non-Significant
OC	:	Organic Carbon
OM	:	Organic Matter
P	:	Phosphorus
PD	:	Particle Density
pH	:	Puissance d'Hydrogen

ppm	:	Parts per million
q ha ⁻¹	:	Quintal per hectare
RBD	:	Randomized Block Design
RDF	:	Recommended Dose of Fertilizers
SOM	:	Soil Organic Matter
viz.	:	<i>Videlicet</i> (namely)
IUCN	:	International Union for Conservation of Nature

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Chapter - 1

INTRODUCTION

Forests are valuable resource of a country which contributes substantially to its economic development. But its exploitation in the last few decades has led to marked shrinkage in the forest cover of the country. Extensive denudation of the forest in the hills has reduced the vegetative cover of Himalayan watershed significantly. Unrestricted urbanization, development activities and increase in human population has exerted a tremendous pressure on forests causing their shrinkage at much faster rate.

Pinus gerardiana Wall., commonly referred to as ‘chilgoza’ or neoza pine, is known by various names in different regions. In Kinnaur, it is called ‘Ree,’ while in Chamba, it is termed ‘Miri.’ In Kashmir, it is recognized as ‘Kashti’ or ‘Galboza,’ and in Afghanistan, it is known as ‘Chilgoza’ or ‘Jhalgoza.’ (Anonymous, 2018). It was first discovered by Captain Patrick Gerard, a British Army officer, in 1932 (Farjon, 1984). This species thrives at elevations of 1800–3300 meters and has a natural distribution spanning eastern Afghanistan, Pakistan, northwestern India, Tibet, and the Xizang Province of China (Critchfield and Little, 1966; Bonner and Karrfalt, 2008; Peltier and Dauffy, 2009; Thakur *et al.* 2012; Thomas, 2019; Singh *et al.* 2021). In India, it is predominantly found in the states of Himachal Pradesh and Jammu & Kashmir. In Himachal Pradesh, chilgoza pine is largely restricted to the districts of Kinnaur and Chamba. The species thrives in arid, temperate regions of the northwestern Himalayas and is valued for its high-quality edible seeds (Dogra, 1964). According to the classification in A Revised Survey of the Forest Types of India (Champion and Seth, 1968), it belongs to Group 13: Himalayan Dry Temperate Forests (C2a). Chilgoza pine is both ecologically and economically significant but has a limited distribution. Out of the total 2060 ha⁻¹ under this species in Himachal Pradesh, 2040 ha⁻¹ are located in Kinnaur district, with only 20 ha⁻¹ in Chamba district. These forests are a major source of chilgoza dry nuts in India (Kumar *et al.* 2013; Troup, 1921). In Kinnaur, chilgoza forests are dispersed across the Kalpa, Kilba, Moorang, and Pooh Ranges (Kumar *et al.* 2013). In Chamba, they are confined to Pangi (in Luj and Dharwas) and Bharmour (in Arki and Suhaga) (Prakash *et al.* 2023). Beyond Himachal Pradesh, its distribution extends westward to the Kishtwar and Astor regions of Jammu and Kashmir (Dogra, 1964; Critchfield and Little, 1966). This restricted distribution highlights the ecological uniqueness and importance of conserving this valuable species.

Pinus gerardiana is a small- to medium-sized evergreen tree that typically reaches a height of 17 to 27 meters, with a trunk diameter ranging from 2 to 4 meters (Bhattacharaya *et al.* 1988). Its branches are short, horizontally oriented, and covered with smooth, silver-gray bark (Kumar *et al.* 2013). The tree has needle-like, dark green leaves arranged in clusters of three. Male cones are longer than the ovoid female cones, which are protected by hard, woody scales (Bhardwaj *et al.* 2022). At maturity, the cones become nearly spherical and dark brown in color (Gul *et al.* 2021). The seeds are large, wingless, cylindrical, and pointed at the tip, with a dark brown hue. They typically mature in October (Peltier and Dauffy, 2009). This species thrives in areas characterized by low rainfall, high winter snowfall, and summer temperatures that do not exceed 35°C (Chandy, 2002; Singh *et al.* 2009). A single chilgoza cone yields between 30 and 118 seeds, and each tree can produce a significant number of seeds depending on climatic factors (Moosavi *et al.* 2022).

Chilgoza pine plays a significant role in the economy of tribal communities in the Kinnaur and Chamba districts of Himachal Pradesh (Sehgal & Khosla, 1986). The edible nuts, or kernels, are highly nutritious, containing carbohydrates (21.6%), proteins (15.9%), lipids (49.9%), moisture (7.5%), fiber (2.2%), and minerals (2.9%) (Kumar *et al.* 2016; Malik *et al.* 2012). On average, a single tree produces approximately 7.4 kg of nuts annually. In tribal households, chilgoza is harvested from nearby forests during September and October. Selling these nuts locally provides an income of INR 1,500–1,800 per kg, helping families meet their financial needs (Lata *et al.* 2020). Chilgoza nuts, marketed as dried fruit, are in high demand, with an annual production of 80–100 tons from Kinnaur alone, generating an export value of around INR 180 million (Negi, 2002). The income from chilgoza contributes between 5 per cent and 25 per cent of the total household earnings, and in some cases, this figure can exceed 25 per cent (Peltier and Dauffy, 2009). Beyond nuts, other parts of the chilgoza tree serve diverse purposes in tribal communities, including timber, fuelwood, torchwood, agricultural tools, household items, traditional medicines, food, beverages, detergents, and farmyard manure (Lata *et al.* 2020). The tree is also valued for its ability to prevent soil erosion and stabilize slopes, which helps mitigate landslides and protect watersheds in the Himalayan region (Gazender *et al.* 2021; Rahimzadeh, 2020; Akbar *et al.* 2014). Its ecological and economic contributions make chilgoza pine a vital resource for these communities. *Pinus gerardiana* faces significant threats due to overexploitation, poor regeneration, habitat fragmentation, and the potential impacts of climate change, leading to its classification as Near Threatened by the IUCN due to a declining population (Farjon,

2013). Unregulated harvesting of chilgoza nuts, where nearly all mature cones are collected by indigenous communities, has severely hindered regeneration and reduced future crop productivity (Tandon, 1963; Singh *et al.* 1973; Sehgal and Sharma, 1989; Thakur *et al.* 2011; Lata *et al.* 2020; Malik *et al.* 2012; Peltier and Dauffy, 2009; Sharma *et al.* 2010). In Himachal Pradesh, particularly in Kinnaur, chilgoza forests have experienced a drastic reduction in area. The total coverage was estimated at 3,278 ha⁻¹ in 1993 (Sharma and Minhas, 1993), which decreased to 2,845 ha⁻¹ by 2001 (Negi, 2017) and further declined to approximately 2,040 ha⁻¹ by 2011 (Sharma *et al.* 2010). Earlier reports suggest that these forests had already shrunk by around 2,000 ha⁻¹ by 1973 (Singh *et al.* 1973). Factors such as excessive cone collection, grazing, browsing, changes in land use, and development activities have all negatively impacted the regeneration of *P. gerardiana* (Singh *et al.* 1973; Sehgal and Sharma, 1989; Malik *et al.* 2012).

The construction of hydropower dams, unplanned infrastructure such as roads, hotels, residential buildings, and other projects destabilize slopes and harm the environment, further reducing the species' distribution and damaging the ecological balance of the Kinnaur region (Sarkar, 2008; Yadav, 2009; Wang *et al.* 2019). Additionally, in Afghanistan, illicit logging for firewood and smuggling, poor forest management, insufficient community involvement, land conversion for agriculture and urbanization, and inadequate investment in reforestation have exacerbated the decline of chilgoza pine forests (Moosavi *et al.* 2022).

Regeneration is essential for the sustainability of forest ecosystems and individual species (Malik and Bhatt, 2016) and plays a critical role in effective forest management (Ahmadi *et al.* 2016). The long-term survival of forest communities heavily depends on successful species regeneration (Saikia and Khan, 2013). The regeneration status of a forest is often assessed by the density of seedlings, saplings, and trees in lower girth classes (Maua *et al.* 2020). Healthy regeneration is indicated by a high density of seedlings and saplings, along with young trees in smaller girth classes, while the absence of seedlings suggests a lack of regeneration (Pokhriyal *et al.* 2010; Chaturvedi *et al.* 2017; Sharma *et al.* 2018). Chilgoza pine primarily regenerates naturally when seeds are released from cones and dispersed. However, excessive cone harvesting significantly hampers natural regeneration (Kumar *et al.* 2016). Even under natural conditions, regeneration is a slow process (Rahimzadeh, 2020). The species exhibits low seed viability and germination rates, with seedlings often affected by factors such as insufficient soil moisture and high temperatures (Malik *et al.* 2012; Kumar

et al. 2013). In Kinnaur, natural regeneration rates vary between 7.5 per cent and 26.5 per cent, averaging around 15 per cent (Malik *et al.* 2012). Other factors contributing to poor regeneration include arid conditions, low soil nitrogen, and extreme weather patterns (Aziz *et al.* 2017). Additionally, drought, temperature fluctuations, and desiccating winds further reduce regeneration success (Kumar *et al.* 2016). The species also faces challenges such as irregular seed production years, seed dormancy, seed-borne fungal infections, and a hard seed coat, all of which hinder natural regeneration (Malik and Shamet, 2008; Khan *et al.* 2021). Due to these limitations, young trees are sparse or entirely absent in chilgoza pine habitats, with mature and overmature trees dominating the landscape (Sharma *et al.* 2010).

Male and female cones of *P. gerardiana* are borne on the same tree but develop separately. Pollination is wind-driven and typically occurs in May or June (Kumar *et al.* 2017; Shalizi *et al.* 2016; Moosavi *et al.* 2022). Trees must reach approximately 30 years of age before they begin producing cones and seeds (Chandy, 2002). Female cones, which contain seeds, are produced during the spring and mature in the autumn of the following year, at which point the seeds are released (Shalizi *et al.* 2016).

The growth and development of chilgoza pine are closely linked to environmental factors, particularly precipitation between March and July, while high pre-monsoon temperatures—except in January, February, and October—negatively affect its development (Kumar *et al.* 2013; Singh *et al.* 2009). Due to its longevity and sensitivity to temperature variations, this species is valuable for millennia-long climatic reconstructions to better understand Himalayan climate variability (Singh and Yadav, 2007). Chilgoza pine forests also play a crucial ecological role in regulating river and stream flow in specific regions (Harmon *et al.* 1986; Bilby and Bisson, 1998). The pine tree grows in association with various other species, including *Cedrus deodara*, *Pinus wallichiana*, *Juniperus polycarpos*, and *Fraxinus xanthoxyloides* at higher altitudes, and *Quercus ilex*, *Olea cuspidata*, and *Alnus nitida* at lower elevations (Ahmed and Latif, 2007 in Pakistan; Peltier and Dauffy, 2009; Lata *et al.* 2020; Kumar *et al.* 2015; Prakash *et al.* 2021 in India). Known as the "Champion of Rocky Mountains," chilgoza pine is adapted to harsh growth conditions, thriving in minimal soil under cold, dry climates with low rainfall and significant snowfall in winter (Malik *et al.* 2012; Singh *et al.* 2009).

The species primarily grows in sandy loam and silty loam soils (Kumar *et al.* 2015; Lata *et al.* 2020). It can adapt to soils with electrical conductivities, CaCO₃ content, low

organic matter, and pH levels between 6.51 and 7.62. Chilgoza pine thrives in soils with moisture levels ranging from 7.97 per cent to 35.34 per cent, nitrogen content from 0.15 per cent to 0.93 per cent, organic carbon content from 4.41 per cent to 5.97 per cent, organic matter content from 7.60 per cent to 10.29 per cent, C/N ratios from 4.97 to 31.97, phosphorus levels between 0.026 and 0.071 mg kg⁻¹, and potassium content from 4.00 per cent to 7.78 per cent (Gul *et al.* 2021; Kumar *et al.* 2016a; Prakash *et al.* 2021; Ahmed *et al.* 1991; Shalizi *et al.* 2016; Kumar *et al.* 2017). The chilgoza pine is an excellent soil binder, stabilizing weak, erodible strata in dry temperate and semiarid climates, thereby mitigating erosion and preventing land degradation (Kant *et al.* 2005; Malik *et al.* 2013; Aziz *et al.* 2017). Analyzing the vegetation of forest ecosystems provides essential insights into population structure, which varies across species and girth classes (Sahu *et al.* 2019). A population structure characterized by fewer seedlings and saplings compared to mature trees signifies poor regeneration, whereas an absence of seedlings indicates a complete lack of regeneration within the forest (Rahman *et al.* 2011).

Therefore, forest stand structure and regeneration status are critical indicators of ecosystem health and biodiversity conservation (Rahman *et al.* 2019). For *P. gerardiana*, the lower prevalence of young trees compared to mature ones is attributed to the combined effects of biotic and abiotic pressures (Kumar *et al.* 2017). Intense biotic pressure has significantly hampered its growth in Himalayan forests, emphasizing the urgent need for sustainable management practices for this species (Urooj and Jabeen, 2015; Kumar *et al.* 2015). Moreover, associated species like *Cedrus deodara* are regenerating and expanding more rapidly than chilgoza pine, potentially threatening its dominance in the future (Kumar *et al.* 2013). The population status and ecological traits of *P. gerardiana* are vital for creating effective conservation strategies, facilitating long-term monitoring, and ensuring sustainable utilization (Prakash *et al.* 2021).

Numerous studies have been conducted to evaluate the population ecology and regeneration patterns of chilgoza pine, providing valuable insights for conservation and management efforts (Peltier and Dauffy, 2009; Sharma *et al.* 2010; Malik *et al.* 2012; Haq *et al.* 2013; Kumar *et al.* 2016; Shalizi *et al.* 2018; Prakash *et al.* 2021).

Keeping in view the various aforesaid points, an investigation entitled “Population dynamics and stand structure of *Pinus gerardiana* Wall. in dry temperate forest of Himachal Pradesh” is critical for understanding the ecological, economic, and conservation challenges

associated with this species. It provides insights into its growth patterns, regeneration capacity, and the factors influencing its survival, which are vital for formulating sustainable management strategies. This present study completed with the following main objectives:

1. To study the morphological variation and stand characteristics of chilgoza pine.
2. To study the phytosociology of chilgoza pine in dry temperate forest of Himachal Pradesh.
3. To study the natural regeneration status and soil nutrient dynamics in different chilgoza pine forests.
4. To study the socio-economic status of chilgoza nut collectors.
5. To assess the genetic diversity of chilgoza pine genotype using DNA based molecular markers.

Chapter - 2

REVIEW OF LITERATURE

This chapter presents a comprehensive analysis of existing research on *Pinus gerardiana* and related species, with a focus on morphological traits, stand structure, phytosociology, natural regeneration, soil nutrient dynamics, socio-economic significance, and molecular studies. The review synthesizes available literature, identifying key challenges and knowledge gaps to better understand the factors influencing the species' sustainability. Although dedicated studies on Chilgoza pine are scarce, insights from related species provide valuable guidance for its conservation and management. Relevant cross-references have been incorporated under the following key headings:

- 2.1 Morphological traits and stand structure**
- 2.2 Phytosociological insights**
- 2.3 Natural regeneration and soil nutrient interactions**
- 2.4 Socio-economic relevance**
- 2.5 Advances in molecular research**

2.1 Morphological traits and stand structure

Morphological characters are plant traits that can be observed, measured, or quantified using various techniques. They are essential for tree growth and development. The following is a summary of the literature on morphological traits, including growth characteristics, needle features, cone and seed attributes, and their genetic analysis.

Researchers have utilized needle traits in conifers, including length, width, stomatal count per row, resin canal number, and morphological variations, to distinguish geographic differences within the genus. (Wright,1976).

Kageyana *et al.* (1977) assessed a progeny trial of *Pinus oocarpa* and observed significant variability in plant height and stem form. Their findings indicated that genetic differences among provenances had a minimal impact on overall phenotypic variation in traits such as diameter over bark and bark thickness.

Xiang *et al.* (2003) analysed genetic parameters for growth traits in loblolly pine (*Pinus taeda* L.) using data from 275 parents and 690 full-sib families across 23 diallel tests in three U.S. regions. Additive variance exceeded dominance variance, which accounted for 20–40 per cent of total genetic variance. Heritability increased over time, with similar trends for DBH, volume, and height. Age-age genetic correlations for height and 8-year volume stabilized after 3–4 years, with DBH and volume

showing stronger correlations. The optimal selection age was 3 for height and 4–5 for DBH and volume, maximizing genetic gain.

Liu *et al.* (2012) assessed genetic variation in growth, morphology, and resin yield in 45 half-sib families of eight-year-old *Pinus massoniana*. All traits showed significant family effects, with the highest individual heritability for DBH (0.55). Heritability for resin yield, tree height, crown depth, and height to the live crown ranged from 0.32 to 0.45, while other traits had weaker genetic control (0.17–0.20). Resin yield was genetically correlated with all growth and morphological traits, with the strongest correlations observed for the number of living branches (0.99), DBH (0.73), and number of living whorls (0.70). The findings suggest that resin yield and growth can be improved simultaneously, with DBH being the best trait for indirect selection of high-yielding resin trees.

Kumar *et al.* (2022) evaluated high resin-yielding half-sib families of *Pinus roxburghii* for growth traits in Shilli Conservation Reserve, Solan, Himachal Pradesh, during 2020–2021. Significant variation was observed in diameter at breast height (31.10 cm), height (17.79 m), bark thickness (2.81 cm), crown length (10.75 m), and crown height (6.95 m). Genetic parameters, correlation studies, PCA, and divergence analysis revealed high variability among families. The study highlights the importance of evaluating *Pinus roxburghii* diversity for improving both qualitative and quantitative traits.

Bhat *et al.* (2016) studied genetic variability in needle and wood traits among half-sib progenies of *Pinus roxburghii*. Significant variation was observed in needle length (18.1–24.6 cm), needle thickness (0.53–0.71 mm), stomatal density (7.3–12.0 per mm), wood specific gravity (0.36–0.46), tracheid length (1.51–1.85 mm), and wood moisture content (47.76–58.81%). High heritability and genetic gain for traits like needle thickness, wood specific gravity, and tracheid length suggest strong genetic control. Correlation studies provided insights for breeding strategies to enhance productivity through indirect selection.

Chauhan and Kanwar (2001) investigated variability and trait associations in *Pinus roxburghii* plus trees for cone and seed characteristics across different forest divisions in Himachal Pradesh. Forty-nine high-growth and high-resin-yield trees were analyzed, revealing significant variation in all studied traits. Higher genetic and phenotypic coefficients of variation, heritability, and genetic advance were observed for cone weight, seed count per cone, and 100-seed weight. Seed length, width, and thickness, along with cone width and weight, had a positive direct influence on 100-seed weight, while cone length and seed count per cone exhibited negative direct and indirect effects. The study highlights key seed and cone traits influencing seed yield.

Wang *et al.* (2018) analyzed the growth traits of 31-year-old *Pinus koraiensis* trees from 42 half-sib families. Nine growth traits were evaluated, including tree height, diameter at breast height

(DBH), volume, basal diameter, annual height growth, under branch height, stem straightness, form quotient, and branching angle. Significant differences were found among families for most traits except form quotient. The phenotypic coefficient of variation for growth traits ranged from 7.17 per cent to 42.35 per cent, with heritability values between 0.13 and 0.62. Strong positive correlations were observed among tree height, DBH, volume, basal diameter, and annual height growth. Based on comprehensive evaluation, four families (PK 40, PK 80, PK 42, and PK 71) were identified as elite for growth performance, contributing to the genetic improvement of *P. koraiensis*.

Xu *et al.* (2014) studied the intraspecific variation of *Pinus yunnanensis* in southwestern China by analyzing morphological differences in needle and cone traits across 18 natural populations. Significant variation ($p < 0.01$) was observed both among and within populations, with over 50% of the phenotypic variation occurring within populations. Needle traits exhibited higher variability than cone traits and were influenced by geo-climatic factors such as latitude, altitude, temperature, and precipitation. Clinal variation was observed in needle length and its ratio to fascicle sheath length along latitudinal and altitudinal gradients. A hierarchical classification based on needle traits grouped populations into four major clusters. These findings provide valuable genetic insights for managing the diversity of *P. yunnanensis*.

Xiang and Isik (2002) analyzed growth traits (height, DBH, and volume) in *Pinus taeda* using data from 275 parents and 690 full-sib families across three test regions in the southeastern U.S. Genetic variance components, heritabilities, and age-age genetic correlations were estimated up to age 8. Additive variance was greater than dominance variance, which accounted for 20–40 per cent of total genetic variance. Heritability generally increased over time, with DBH and volume showing comparable heritability to height. Age-age genetic correlations for early height with 8-year volume rose significantly in the first 3–4 years before stabilizing, with DBH and volume showing stronger correlations than height. The findings suggest that optimal selection could begin as early as age 3 for height and age 4 for DBH and volume, with volume selection at age 4–5 maximizing genetic gain.

Barbeito *et al.* (2008) analyzed the spatial structure of even-aged and uneven-aged *Pinus pinea* stands in Spain to understand regeneration patterns. Using a grid-based crown projection method alongside traditional point pattern analysis, they found that regeneration was clumped in both stands, with spatial associations varying by age class. Crown pattern analysis provided better insights, especially in older stands with larger crowns. The study highlights the importance of considering crown dimensions to avoid misinterpretations and improve regeneration management strategies.

Garcia-Abril *et al.* (2007) examined the relationship between competition and tree growth in four *Pinus sylvestris* stands in the Guadarrama range, Spain. A size-ratio competition index showed a negative association with tree diameter, strongest in uneven-aged, plantation, and mature even-aged

stands. Competition also negatively affected diameter growth, with a stronger effect in mature even-aged stands and a weaker effect in uneven-aged stands and plantations. Diameter and basal area growth were higher in uneven-aged than in even-aged stands, and the competition index was a better predictor of growth rate than diameter alone.

Singh and Gupta (2008) conducted a study on the growth and standing volume estimation of *Cedrus deodara* stands in Himachal Pradesh. Their findings indicated that parameters such as diameter, height, bole height, and crown width increased as tree diameter increased. However, the number of individuals showed a declining trend with increasing diameter.

Sharma and Raina (2013), while examining the composition, structure, and diversity of tree species along altitudinal gradients in the northwestern Himalayas, observed that the higher elevations (2000–3250 m asl) were predominantly occupied by temperate coniferous species such as Kail, Deodar, Fir, and Spruce. In their study, *Cedrus deodara* exhibited the highest total basal area (72.80 m²/ha), followed by *Acacia modesta* (65.43 m²/ha), *Quercus semicarpifolia* (62.34 m²/ha), and *Quercus leucotrichophora* (58.78 m²/ha). Regarding tree density, *Cedrus deodara* recorded the highest density (675 trees/ha), followed by *Pinus roxburghii* and *Pinus wallichiana*, each with 625 trees/ha.

Digvijay *et al.* (2015) assessed the diameter, height, and density of *Cedrus deodara* across 10 blocks in the Uttarakhand Forest subdivision while studying variations in volume, biomass, and carbon stocks in different deodar forests of the Garhwal Himalaya. Their findings showed that the maximum diameter at breast height (DBH) for *Cedrus deodara* was recorded in Kanasar (57.07±2.15 cm), while the minimum was observed in Dhanolti (42.10±2.15 cm). The highest average tree height was found in Kanasar (37.64±0.95 m), whereas the lowest was recorded in Harshil (19.68±0.45 m). The study also indicated that *Cedrus deodara* density varied across sites, with the highest stand density in Jakholi Jwarnath (410.0±7.9 individuals/ha) and the lowest in Dandachalli (227.0±3.3 individuals/ha).

Chandra (2009) studied the tree species composition, regeneration, and diversity in a miscellaneous forest located in the Tarai region of Kumaon Himalaya. The study reported a tree basal area ranging from 2325.0 to 2974.7 cm², with a density of 4.7 to 7.0 plants per 100 m² in the tree layer. Sapling density varied between 8.0 and 18.4 individuals per 100 m², while seedling density ranged from 58.8 to 146.3 individuals per 100 m². The Shannon-Wiener diversity index for the tree layer was recorded between 2.408 and 2.862, with a dominance concentration ranging from 0.163 to 0.205 and equitability values between 8.58 and 11.23. The study identified four distinct population structure patterns. *Mallotus philippensis* exhibited an expanding population structure, whereas *Dalbergia sissoo* showed a lack of lower girth classes, suggesting its regeneration was hindered by

increasing forest density. *Tectona grandis* and *Cassia fistula* were represented only by seedlings, indicating their recent establishment in the area.

Dutta and Devi (2013) investigated the floristic composition of protected tropical forests in Assam, northeast India. The study covered four reserve forests—Lumding (LRF), Doboka (DRF), Hojai (HRF), and Kumorakata (KRF)—in the southern part of Nagaon district. Phytosociological data were collected using the quadrat method during 2009-2010, with stratified random sampling. A total of 208 species (82 trees, 32 shrubs, 94 herbs) from 165 genera and 71 families were documented. LRF had the highest species count (117), while KRF recorded the lowest (69). Euphorbiaceae was the most dominant family (16 species), followed by Poaceae (13 species). LRF was dominated by *Trewia nudiflora* and *Bauhinia variegata*, while *Shorea robusta* along with *Dillenia pentagyna* and *Careya arborea* were prevalent in DRF and HRF. In KRF, *Ficus nervosa* was the dominant tree species. Tree diversity, measured using the Shannon-Wiener index, ranged from 3.63 (LRF) to 1.52 (HRF). DRF and HRF exhibited the highest similarity index, likely due to the shared dominance of *Shorea robusta* and its associated species. Variations in dominant species were attributed to differences in disturbance levels, forest types, and elevation.

Aye *et al.* (2014) examined the floristic composition, diversity, and stand structure of four natural tropical forests in Popa Mountain Park, Myanmar. These forests included dry mixed deciduous, dry dipterocarp, dry forest, and dry hill/evergreen forest. Stem density varied from 1293 trees per hectare in the dry dipterocarp forest to 804 trees per hectare in the dry evergreen forest. The highest species richness was recorded in the dry mixed deciduous forest (74 species per hectare), while the dry forest had the lowest (40 species per hectare). The dry mixed deciduous forest exhibited the highest Shannon-Wiener and Simpson diversity index values, indicating its structural complexity, whereas the dry forest had the lowest, suggesting it was the least diverse community.

Pilania *et al.* (2014) analyzed species diversity and phytosociology in the tropical dry deciduous forests of Dahod district, Gujarat, India. The study identified 65 species from 57 genera across 31 families, with Mimosaceae being the most dominant family. The Importance Value Index was calculated, revealing that most species exhibited a contagious distribution based on the abundance-to-frequency ratio. The concentration of dominance ranged from 0.08 to 0.52, while Shannon's diversity index varied between 0.81 and 2.85. Species evenness was recorded between 0.7 and 0.93, and species richness ranged from 2.8 to 30.84.

Neelo *et al.* (2015) investigated the stand structure, diversity, and regeneration status of woody species in open and enclosed woodland sites in Botswana. The study documented 47 species from 24 genera and 16 families, with *Acacia* being the most diverse genus. Regeneration was found to be largely hindered, leading to an unhealthy growth pattern in most species. Factors such as human disturbances and excessive overgrazing were identified as the primary causes of poor regeneration.

Malik and Bhatt (2016) studied tree regeneration and seedling survival along an altitudinal gradient in the Western Himalaya, India. They recorded 44 species from 36 genera and 25 families. Regeneration was assessed through seedling and sapling populations, while survival was measured using silver foil tagging. Seedling density ranged from 1,670 to 7,485 individuals per hectare, and sapling density from 1,850 to 5,600. Most species (27-56%) showed good regeneration, while others had poor (19-45%), fair (7-30%), or new (0-14%) regeneration. Diameter distribution followed an inverse-J curve, indicating strong regeneration. Seedling survival varied from 0-8 per cent, with mortality rates between 12-100 per cent.

Khan et al. (2013) studied the phytosociology, structure, and dynamics of *Pinus roxburghii* in 40 stands across northern Pakistan using cluster analysis and ordination. Three major community types were identified: *P. roxburghii*, *Pinus-Quercus baloot*, and *Pinus-Olea ferruginea*. Elevation and slope were key factors influencing species distribution, along with soil chemistry. The total tree density was 14,700 plants/ha, with *P. roxburghii* contributing 82–100 per cent. However, low juvenile density and gaps in size-class distribution indicated poor recruitment due to browsing, logging, and human activities. Despite these challenges, *P. roxburghii* showed the fastest growth among conifers, making it a viable option for short-term wood production in the Lesser Himalayas and Hindukush ranges.

Peri *et al.* (2024) analyzed the stand structure of *Pilgerodendron uviferum* relicts in Santa Cruz, Argentina. They found significant variation among four studied relicts, with two associated with *Nothofagus antarctica* exhibiting higher tree density, DBH, and dominant height. These relicts also had greater sapling density (1950–3167 individuals per hectare) and higher understory plant diversity compared to pure *P. uviferum* relicts near the steppe ecotone. The study highlighted slow diameter growth (0.33–0.46 mm per year), suggesting a stress-tolerant strategy. This information is valuable for conserving fragmented *P. uviferum* forests.

2.2 Phytosociological Insights

Phytosociology examines the characteristics, classification, relationships, and distribution of plant communities. Gathering such data is essential for understanding species population dynamics and their interactions within the same community. Vegetation plays a crucial role in shaping ecosystem structure and function, influencing various ecological factors, including microclimate, energy balance, photosynthesis, water cycles, runoff, and soil properties (Tappeiner and Cernusca, 1996). Vegetation differs across regions based on habitat heterogeneity. The species richness in an area reflects the gene pool and the community's adaptation potential, while quantitative analysis provides insights into its structure, composition, and trophic organization (Odum, 1963). Species diversity and composition vary across habitats and within communities that exhibit similar physiognomic traits (Nautiyal *et al.* 1999). Factors such as topography, elevation, soil, rainfall, and

other climatic conditions influence the presence of specific plant species, particularly in the Himalayas (Gaur *et al.* 1995). The abundance of species indicates their ability to emerge, grow, and establish under favourable conditions, though this ultimately depends on environmental factors, tolerance levels, and species adaptation (Bhandari *et al.* 1999).

Phytosociological studies have revealed a high level of endemism in *Pinus gerardiana* within its natural habitat. This is reflected in the scarcity or absence of young and middle-aged trees, while mature and over-mature trees dominate these regions. One possible reason for this pattern is that in the past, *Pinus gerardiana* forests in Kinnaur were not heavily exploited for nuts due to their remote location. Additionally, before the partition, the demand for chilgoza pine nuts was largely met by the forests of Baluchistan (Tandon, 1963). Nut-producing pines hold significant economic, ecological, cultural, historical, and spiritual value. They offer numerous benefits, including nutrient-rich edible nuts, durable and aromatic wood, and other valuable resources. However, pine forests have historically been, and continue to be, subject to timber harvesting. The rising global demand for pine nuts highlights the need for improved management of existing resources and investment in pine nut cultivation both within and beyond their native habitats (Richardson, 1998; Sharashkin & Gold, 2004).

Geelani *et al.* (2018) examined the phytosociological status of trees and shrubs in the Romshi range of the Shopian forest division. The findings indicated that *Cedrus deodara* and *Pinus wallichiana* were dominant in the lower elevation, while *Picea smithiana* and *Abies pindrow* prevailed in the middle and upper elevations. Among shrubs, *Parrotiopsis jacquemontiana* was most abundant at lower elevations, whereas *Viburnum grandiflorum* dominated the middle and upper regions.

Adnan Bhat (2017) investigated the phytosociological status of vegetation in Batkote Block, Pahalgam Range, documenting 59 plant species across 37 families, including 11 tree species, 10 shrubs, and 38 herbs. The study revealed that *Pinus wallichiana* was the dominant tree species at lower and middle altitudes, with IVI values of 75.49 and 86.26, followed by *Cedrus deodara* (IVI: 44.69 and 43.38). At higher altitudes, *Abies pindrow* (IVI: 79.00) and *Picea smithiana* (IVI: 52.01) were prevalent. Among shrubs, *Parrotiopsis jacquemontiana* was the most dominant at lower and middle elevations (IVI: 57.41 and 49.69), while *Viburnum grandiflorum* dominated at higher altitudes (IVI: 81.95). For herbs, *Cynodon dactylon* was prevalent at lower altitudes (IVI: 18.65), whereas *Fragaria vesca* was dominant in middle and upper altitudes (IVI: 20.99 and 30.45).

Chilgoza pine is a resilient species, capable of enduring harsh winter cold and prolonged drought. Its adaptability allows it to thrive across much of the dry valleys of the Western Himalayas (Troup, 1921). In Kinnaur district, it has been observed that chilgoza pine gradually replaces chir pine near Wangtu and extends along the Sutlej River up to Dubling village, forming both pure and mixed

forests with deodar (Singh & Singh, 1995). This tree species thrives on dry, rocky hillsides with minimal soil, playing a crucial role in soil conservation, which would otherwise leave these areas barren and rocky (Sharma, 2004). Research by Singh & Yadav (2007) suggests that the growth of chilgoza pine is closely linked to environmental conditions, with precipitation influencing its development, except during January, February, and October. Additionally, studies indicate that climate change could significantly impact the future growth and sustainability of chilgoza pine forests (Bawa *et al.* 2005).

Ahmed and Latif (2007) reported that chilgoza pine grows in small patches in Southern Chitral at elevations ranging from 1,800 to 3,500 meters. At higher elevations, it is found alongside deodar and blue pine, while at lower elevations, it associates with oak. Similarly, a study of 44 forest stands in Baluchistan found that 42 were dominated by chilgoza pine, while the remaining two had a predominance of broad-leaved species. The density of chilgoza pine varied from 24 to 930 trees per hectare, with an average of 266 trees per hectare and a mean basal area of 25.5 m² per hectare (Ahmed *et al.* 1991). Research by Sharma *et al.* (2010) identified chilgoza pine in 14 sites, where it was dominant in 8, occupying 96.46 per cent of the niche, while the remaining space was shared with deodar. This dominance may be attributed to the tendency of temperate Himalayan pine forests to gradually replace broad-leaved species. Additionally, these forests support limited shrub diversity, though ground vegetation flourishes, particularly after fire events, leading to high herbaceous plant diversity compared to other forest types (Rawat & Bhandari, 2006).

Ali (2007) observed that in the Kullu Forest Division, tree density, basal area, and standing volume increased with elevation across all diameter classes. Similarly, Lanker (2007) reported comparable findings, noting an elevation-related increase in these parameters. Mahajan (2010), in a study on chir pine forests in Solan, found that the highest volume occurred in different diameter classes, with 20-30 cm in PB-I, 30-40 cm in PB-IN, and 20-30 cm in PB-IV.

Hawn *et al.* (1999) suggested that altitude and site characteristics play a crucial role in shaping species diversity in mountain forest ecosystems. Zheng *et al.* (1998) found that species diversity increased as forests transitioned from coniferous to broad-leaved mixed types. Additionally, Rikhari *et al.* (1997) reported that in the mixed oak forests of Kumaon Himalaya, *Quercus leucotrichophora* was dominant on the eastern slopes, whereas *Q. floribunda* was more prevalent on the northwestern slopes.

At the base of the hills and on the eastern slopes, *Quercus floribunda* and *Quercus leucotrichophora* exhibited similar dominance, though in other eastern stands, *Q. leucotrichophora* was more prevalent. A phytosociological study by Pandey (2003) conducted along an altitudinal range of 1,500 to 2,000 meters in the Kumaon Himalaya identified various forest communities based on Importance

Value Index (IVI). These included chir pine, deodar mixed with chir pine, chir pine mixed with oak, and oak-dominated mixed broad-leaved forests. Chir pine was found to be the dominant species at lower elevations, while *Q. leucotrichophora* prevailed at higher altitudes.

Singh (2004) conducted a vegetation survey in the Tirthan Valley of Kullu district, Himachal Pradesh, and observed distinct plant community compositions between aspects. The northern slopes were dominated by *Cedrus deodara*, *Abies pindrow*, and *Picea smithiana*, whereas the southern slopes were primarily composed of *Pinus wallichiana*, *Rhododendron arboreum*, and *Quercus semecarpifolia*. The density of *Picea smithiana* and *Abies pindrow* was greater on north-facing slopes compared to the southern aspects.

Dhaulkhandi *et al.* (2008) studied natural forest communities in Gangotri, Uttarakhand, and recorded the highest tree density for *Picea smithiana* (240 trees per hectare), while the lowest was found for *Pinus wallichiana* and *Acer caesium* (30 trees per hectare). Among tree species, 65.16 per cent displayed a contagious distribution pattern, while 34.84 per cent were randomly distributed, with none exhibiting a regular distribution pattern.

Gupta (1996) conducted a phytosociological and biomass study of fir-spruce forests in Narkanda and Chhachpur, revealing that *Cedrus deodara* had the highest Importance Value Index (IVI), recorded at 48.26 in Chhachpur and 78.70 in Narkanda. Additionally, the IVI value of *Abies pindrow* increased with elevation in both regions. It was observed that the characteristics of deodar trees—such as diameter at breast height (DBH), basal area, height, age, volume, mean annual increment (MAI), and the densities of trees, shrubs, and herbs—were generally higher at lower elevations than at higher altitudes. Similarly, Shamet *et al.* (1999) examined the structural characteristics of *Taxus baccata* within fir-kharsu oak forests. Their study found that fir forests had the highest relative density (14.7), relative frequency (16.22), and relative basal area (3.0), followed by kharsu oak and deodar forests.

Lee *et al.* (2000) analyzed the vegetation composition in central Taiwan at elevations ranging from 2,500 to 3,952 meters above sea level. Their study identified various vegetation types, including alpine grasslands, *Pinus taiwanensis* (Taiwan hemlock), *Taxus sumatrana* (Taiwan yew), *Chamaecyparis formosensis* (Formosan red cypress), *Picea morrisonicola* (Taiwan spruce), *Abies kawakamii* (Taiwan fir), *Juniperus squamata* (high mountain juniper), and alpine tundra communities. Among these, Taiwan hemlock was the dominant species, with a diameter at breast height (DBH) ranging from 5 cm to 230 cm and an age range of 20 to 950 years.

Sharma (2006) reported that *Abies pindrow* exhibited the highest dominance (IVI 261.05) at elevated locations in the Jubbal and Bashla forests. Similarly, Lanker (2007) studied the edapho-

ecological features of yew in Kotgarh, Chopal, and Theog Forest Divisions of Himachal Pradesh, noting that *Picea smithiana* was most dominant in the Baggi forest compared to other locations. Ali (2007) also conducted a phytosociological study in the Kullu Forest Division, finding *Picea smithiana* as the dominant species in Sarsai and Sojha forests, with IVI values of 120.11 and 74.60, respectively. Mahajan (2010), in an investigation of chir pine forests in Solan district, identified *Pinus roxburghii* as the most dominant species across all periodic blocks. In mixed forests, chir pine exhibited 100% frequency, with the highest value among all tree species across the different periodic blocks.

Lanker (2007) reported that *Viburnum cotinifolium* was the dominant shrub species across nearly all sites in the Theog Forest Division. Similarly, Ali (2007) found that *Prinsepia utilis* was the most prevalent shrub in all study sites within the Sarsai forest of Kullu Forest Division. In contrast, Gupta (2007) identified *Berberis aristata* as the dominant shrub species in the Rajgarh forest of Sirmour district.

Ali (2007) also observed that tree species similarity in Kullu Forest Division was highest (85.70%) between Ramsu lower and Sarsai upper, as well as between Ramsu upper and Ramsu lower. For shrubs, the greatest similarity (80.00%) was recorded between the upper and lower elevations of the Sarsai forests. Likewise, Mahajan (2010) found that tree species similarity among different periodic blocks exceeded 45 per cent, with the highest similarity (57.14%) observed between PB-I and PB-IN, as well as PB-I and PB-IV, within mixed forests.

Mahajan (2010) reported that solar intensity was highest in lower diameter classes, while the leaf area index (LAI) tended to be greater in larger diameter classes. Additionally, organic carbon, nitrogen, and phosphorus were more concentrated in the upper soil layers, whereas pH and potassium were higher in the deeper soil layers.

2.3 Natural Regeneration and Soil Nutrient Interactions

Evaluating natural regeneration is crucial for shaping production and management strategies in forest ecosystems (Greene *et al.* 1999). This becomes particularly significant when preparing or revising working plans (Liira and Sepp, 2009). The primary goal of such assessments is to determine whether forest regeneration is adequate or insufficient (Hanssen, 2003).

Gordon (1970) examined the natural regeneration of *Abies concolor* and *A. magnifica* in the forests of northeastern California, reporting that regeneration was successful when seeds were viable, mineral soil was exposed, and partial shade was present. However, challenges such as excessive sunlight exposure, thick litter layers, competition from lower vegetation, and irregular seed production hindered seedling survival and growth. Similarly, Singh (1973) observed that factors like thick raw humus layers, dense weed cover, grazing, human disturbances, and poor drainage negatively impacted

the natural regeneration of silver fir. The regeneration of Engelmann spruce was found to be influenced by weather conditions, aspect, and seedbed characteristics. Nobel and Alexander (1977) reported that small clear-cut openings of 1-2 ha⁻¹ on north-facing slopes could regenerate successfully with minimal shade, while regeneration on south-facing slopes was not viable without significant shading. Additionally, Sorg (1980) noted that in subalpine spruce forests, regeneration density increased with steeper slopes and higher pH levels in the top humus layer.

Kumar *et al.* (2015) studied the regeneration dynamics of *Pinus gerardiana* in the dry temperate forests of the North-Western Indian Himalaya. The research highlighted the dominance of *P. gerardiana*, followed by *Cedrus deodara*, *Pinus wallichiana*, and *Quercus ilex*. Regeneration success varied across sites (8.44%–15.93%) and was influenced by factors like seed cone collection, grazing, and soil properties. The distribution of seedlings, saplings, and trees was uneven, with many sites showing poor regeneration. The study emphasized the need for further surveys to identify conditions that promote sustainable regeneration of *P. gerardiana*.

Natural regeneration of chilgoza pine is extremely poor or nearly absent within its native range. One of the primary reasons for this is the extensive collection of cones by local communities (Tandon, 1963; Singh *et al.* 1973). Since the edible nuts are harvested by locals, natural regeneration is severely restricted (Ahmed and Latif, 2007) and is mostly confined to cliff areas or locations with dense shrub cover, where seedlings are shielded from birds and rodents (Chandra and Khushdil, 1977). Additionally, goat grazing significantly hinders natural reproduction, although some seedlings manage to establish themselves under the protection of thorny bushes (Luna, 2008). Even when seedlings survive these biotic pressures, they face harsh environmental conditions, such as intense sunlight, desiccating winds, and limited soil moisture, which contribute to high mortality rates. The species often grows in sandy, shallow, and dry soils with poor water retention, further exacerbating seedling loss during drought periods (Singh *et al.* 1973).

Kumar *et al.* (2016) examined the ecological status of *Pinus gerardiana* in the North-Western Himalaya, highlighting its restricted distribution and regeneration challenges. The species faces threats due to extensive cone/seed collection by locals, leaving only remote and inaccessible trees to contribute to regeneration. The study found a scarcity of young trees, with mature trees dominating the landscape. Phytosociological analysis showed *P. gerardiana* covered over 70 per cent of the area, emphasizing its high endemism. The study stressed the need for conservation measures to ensure the sustainability and productivity of chilgoza pine forests.

Apart from these challenges, chilgoza pine has an irregular and infrequent seed production cycle, along with dormancy-related issues, which reduce its ability to regenerate naturally (Malik and Shamet, 2008). Given the high level of biotic pressure and poor regeneration, the species faces the

risk of population decline and potential extinction in the future (Kumar, 1986; Sehgal and Chauhan, 1989).

Mughal *et al.* (2018) examined the regeneration status of *Picea smithiana* across different altitudinal gradients in the North Kashmir Himalayas. The findings indicated a gradual decline in recruits, seedlings, saplings, and tree density as elevation increased. Based on the analyzed parameters, the study identified the 2,200-2,600m range as the most favorable for *Picea smithiana* regeneration in North Kashmir. The research focused on three altitude zones: 2,200-2,600m (Langate), 2,600-3,000m (Jhelum), and 3,000-3,400m (Kamraj).

Peltier and Dauffy (2009) noted that in Kinnaur district, villagers typically lease out contracts to private contractors, who then employ foreign laborers, primarily from Nepal, to harvest cones by cutting cone-bearing branches. This practice has led to a severe decline in natural regeneration within its native habitat. The financial contribution of chilgoza pine nuts to household income in Kinnaur ranges from 5 per cent to 25 per cent. Due to high market demand, these nuts command premium prices, typically between Rs. 700 and 900 per kilogram. Out of the estimated 800 quintals of nuts produced in Kinnaur, approximately 750 quintals (valued at Rs. 6 crore) are exported to markets across India and even internationally (Anon, 1997; 2002). Consequently, Kinnaur contributes the majority of the country's nut supply, with the remaining demand being met through imports from Afghanistan.

As early as 1937, Glover suggested implementing rotational closures to restrict nut collection and promote regeneration. However, the increasing market value of chilgoza pine nuts has made it challenging to enforce such conservation measures (Reddy, 1963). Lakhanpal and Kumar (1995) recommended that chilgoza pine-bearing areas should remain undisturbed for at least 30 years to ensure the species' survival. Similarly, Luna (2008) observed that in regions where grazing and cone collection were restricted, natural regeneration occurred more successfully.

Hanief *et al.* (2016) studied the natural regeneration dynamics of dominant tree species along an altitudinal gradient across three forest types in the Darhal watershed, located in the northwestern Himalayas (Kashmir), India. The forests were primarily dominated by *Quercus incana*, *Persea duthiei*, and *Abies pindrow*, with a total of 14 tree species recorded. Tree density ranged from 492 to 1,325 individuals per hectare, while the total basal area varied between 25.88 and 188.90 m²/ha.

Singh *et al.* (2016) analyzed tree species richness, diversity, and regeneration in *Quercus*-dominated forests of the Garhwal Himalayas, India. Their findings recorded 18 tree species from 16 genera and 12 families. Species richness varied among trees (4-7), saplings (3-10), and seedlings (2-6). Seedling and sapling densities ranged from 1,376 to 9,600 individuals per hectare and 167 to 1,296

individuals per hectare, respectively. Species diversity indices were between 1.27-1.86 (trees), 0.93-3.18 (saplings), and 0.68-2.26 (seedlings). The total basal area measured 2.2-87.07 m²/ha for trees, 0.20-2.24 m²/ha for saplings, and 299-8,177 cm²/ha for seedlings. The majority (20-80%) of tree species displayed good regeneration, while *Quercus floribunda*, the dominant species, exhibited poor regeneration. This highlights the need for effective management and conservation strategies to ensure the sustainability of *Q. floribunda* and other species facing regeneration challenges.

Gupta (1996) examined the regeneration patterns of fir and spruce in the Narkanda forest, finding that fir exhibited higher regeneration rates (687.5 ha⁻¹) than spruce (312.5 ha⁻¹). Conversely, in Chhachpur forest, spruce regeneration (1,875.0 ha⁻¹) surpassed that of fir (833.3 ha⁻¹). The study further indicated that in Narkanda, regeneration declined with increasing elevation, ranging from 1,250.0 ha⁻¹ to 208.3 ha⁻¹ for fir and from 625.0 ha⁻¹ to 156.3 ha⁻¹ for spruce. However, in Chhachpur, fir regeneration increased with elevation (625.0 ha⁻¹ to 1,041.7 ha⁻¹), while spruce regeneration showed a declining trend (2,083.0 ha⁻¹ to 1,666.7 ha⁻¹). Feller (1998) explored the natural regeneration of subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*), concluding that seedling survival and growth were relatively consistent across different site conditions. The study observed that fir seedlings thrived in increased light exposure, whereas spruce seedlings benefited from partial shade for improved survival.

Shahraji and Yousofpour (2003) reported that yew seedling density was approximately one plant per 10 m², with over 50 per cent of seedlings falling within the 0–5 mm collar diameter range. The largest seedlings, measuring between 15 mm and 20 mm, represented the smallest proportion. Although there was a significant presence of yew recruits on the forest floor, harsh environmental conditions hindered their successful establishment. Similarly, Dhaulkhandi *et al.* (2008) analyzed regeneration trends and found that 71.4 per cent of species exhibited good regeneration, 14.3 per cent faced regeneration challenges, and another 14.3 per cent showed no signs of regeneration.

Malik *et al.* (2012) evaluated the natural regeneration status of *Pinus gerardiana* (Chilgoza pine) in the forests of Kinnaur, Himachal Pradesh, India. The study area was categorized into three zones: dry temperate, semi-arid, and arid. Sampling plots measuring 20 × 20 m were established, with 2 × 2 m quadrats for regeneration assessment placed along the eastern and western banks of the Sutlej River. Findings indicated that the semi-arid zone on the western aspect had the highest regeneration (291.66 plants/ha). However, the overall natural regeneration rate of the species was notably low, averaging just 15 per cent.

Pandey (2003) reported that seedling and sapling densities were notably low for most species, except for pine, which exhibited a gradual expansion over oak and other species across the study area. Conversely, Russell *et al.* (2003) found that tree species regeneration was negatively impacted by

dense canopy cover and deep litter accumulation but showed a positive correlation with solar radiation. Temperature also played a crucial role in the successful regeneration of Scots pine. Varmola *et al.* (2004) noted that regeneration was most effective during extended warm periods lasting at least 20 years, with temperature limits aligning well with the timberline. Similarly, Utsugi *et al.* (2006) observed that elevated air and soil temperatures, along with minimal litter accumulation at the hardwood-conifer boundary, created more favorable conditions for hardwood seed germination and seedling growth compared to the interior of coniferous forests.

Ali (2007) observed that the regeneration of Himalayan yew (*Taxus wallichiana*) was absent in all the selected sites, with only recruits being recorded, while unestablished and established plants were missing in some yew-bearing areas. Similarly, Lanker (2007) found that the highest number of recruits was present in the Baggi and Sidhpur forests of Kotgarh Forest Division, but no unestablished or established regeneration was recorded at any of the selected locations. In contrast, Gupta (2007) reported that fir and spruce forests exhibited good regeneration, with no significant concerns. However, the conversion rate from recruits and unestablished plants to established regeneration was hindered due to biotic disturbances. Mahajan (2010), in his study on Solan forests, noted that the highest regeneration success and established stocking percentage for chir pine were recorded in PB-IV of pure forests, while *Pyrus pashia* showed maximum success in PB-I of mixed forests in Solan Forest Division, Himachal Pradesh.

Prakash *et al.* (2021) studied the regeneration dynamics of *Pinus gerardiana* in the Pangi Range of Chamba, reporting tree densities between 290 and 430 Ind ha⁻¹. The highest was in Luj E (430 Ind ha⁻¹), while the lowest was in Luj A (290 Ind ha⁻¹). Seedling density ranged from 20 to 60 Ind ha⁻¹, with Luj D and Luj G showing the highest (60 Ind ha⁻¹) and Luj B and Luj F the lowest (20 Ind ha⁻¹). Sapling density varied from 0 to 140 Ind ha⁻¹, with Luj D recording the maximum (140 Ind ha⁻¹) and Luj A the minimum (0 Ind ha⁻¹). For *P. gerardiana*, tree density ranged from 170 to 380 Ind ha⁻¹, seedlings from 20 to 60 Ind ha⁻¹, and saplings from 0 to 90 Ind ha⁻¹. The highest tree density was in Luj G (430 Ind ha⁻¹), while the lowest was in Luj F (340 Ind ha⁻¹). Seedlings peaked in Luj G (60 Ind ha⁻¹) and were lowest in Luj B and Luj F (20 Ind ha⁻¹ each). Sapling density was highest in Luj C and Luj D (80 Ind ha⁻¹ each) and lowest in Luj A (0 Ind ha⁻¹).

Malik (2007) studied chilgoza pine and found that the number of recruits, unestablished, and established regeneration was higher on the left (Western) aspect compared to the right (Eastern) aspect. The overall mean establishment stocking was 10.14 per cent, with a regeneration rate of 15 percent on the left bank (Western aspect), whereas the right bank (Eastern aspect) had lower values, with 6.49 per cent establishment stocking and 10.83 per cent regeneration in Kinnaur district.

Ali (2007) studied site factors and found that as elevation increased, soil pH, available nitrogen, and potassium declined, while organic carbon, soil moisture, available phosphorus, and organic matter increased. Similarly, Lanker (2007) observed that soil moisture, organic carbon,

available nitrogen, and available phosphorus decreased with soil depth, whereas soil pH and available potassium exhibited an increasing trend.

Wani *et al.* (2022) studied the regeneration status and soil site characteristics of Spruce (*Picea smithiana* Wall. Boiss) dominated forest along altitudinal gradient in North Indian Himalaya. The regeneration of Spruce at all the sites was low and did not show any definite trend along the altitudinal gradient. There was a decrease in availability of OC, N, P, K, Fe and Zn with increase in soil depth at all the three altitudes. However, soil pH showed the reverse trend. There was an increase in availability of OC, N, P, K and Zn while decrease in pH and available Fe in soil with the increase in altitude. The viability of soil seed bank of spruce was found to be very low (15.36 to 18.18%). The composite soil samples were collected from two depths (i.e., 0–15 cm and 15–30 cm) of the selected altitudes. The soil nutrient analysis was carried out in the laboratory of Faculty of Forestry SKUAST-Kashmir. Soil pH, Organic Carbon (OC), Available nitrogen (N), phosphorus (P), potassium (K), zinc (Zn) and iron (Fe) were determined using ‘Mridaparishak’ a Minilab for Soil Testing developed by ICAR-Indian Institute of Soil Science, Bhopal.

Forest soils are generally recommended to be slightly acidic to maintain a balanced nutrient supply (Leskiw, 1998). The pH levels in undisturbed natural forests are typically lower than those found in disturbed ecosystems (Robertson and Vitousek, 1981; Adams and Sidle, 1987). This decline in pH is often linked to the buildup and gradual decomposition of organic matter, which leads to the release of acids into the soil (Hann, 1977).

Digvijay *et al.* (2015) investigated biomass and carbon stocks in various deodar forests of the Garhwal Himalaya. Their study found that soil pH across all sites ranged from 6.28 to 7.00 at different soil depths, specifically 0–15 cm, 16–30 cm, and 31–45 cm.

Phosphorus plays a crucial role in plant growth and development. In terrestrial ecosystems, it exists in both organic and inorganic forms, with organic phosphorus being the primary available source. The rate of weathering influences phosphorus availability for plant uptake. The phosphorus content in soil determines its suitability for specific plant species and helps in identifying vegetation types in an area. Additionally, phosphorus levels regulate the input of plant residues into the ecosystem (Brown *et al.* 1994).

Bohra *et al.* (2011) studied soil characteristics in oak and pine forests of the Indian Central Himalaya. Their findings indicated that available phosphorus ranged from 42.12 ± 9.07 kg/ha in degraded pine forest sites to 56.00 ± 10.85 kg/ha in non-degraded oak forest sites. They also noted that available phosphorus was more abundant in the lower soil horizons across all forest types and showed a positive correlation with organic carbon while being negatively correlated with altitude.

Potassium exists in an insoluble form in all parts of plants and plays a crucial role in carbohydrate and protein synthesis. It activates plant enzymes, facilitates starch formation, supports nitrate reduction, and contributes to sugar breakdown. Additionally, potassium is essential for regulating key processes such as transpiration and respiration (Brady, 1996). Its availability decreases due to leaching and drainage, which can lead to vegetation loss (Basumatary and Bordoloi, 1992).

The amount of available potassium in soil differs based on forest type or species composition in natural stands. In Himalayan moist temperate forests, available potassium in natural stands of *Abies pindrow* ranged from 107.00 to 260.00 kg/ha (Sharma and Baduni, 2000). Meanwhile, in natural stands of *Quercus floribunda* at Dudhatoli, Pauri Garhwal, it varied between 356.70 and 712.00 kg/ha.

Bhatt *et al.* (2014) analyzed the physico-chemical properties of soil and the influence of climatic factors on vegetation in the Central Himalaya. The study included different forest types such as Pine-Oak Forest, Mixed Oak-Conifer Forest, Mixed Broadleaved-Conifer Forest, and Conifer Forest. Bhatt *et al.* (2000) also documented the average soil moisture content across these forests, reporting values of 18.8 per cent in Pine-Oak Forest, 24.7 per cent in Mixed Oak-Conifer Forest, 26.3 per cent in Mixed Broadleaved-Conifer Forest, and 20.5 per cent in Conifer Forest.

2.4 Socio-economic Relevance

Thomas (1996) analyzed the collection of non-timber forest products (NTFPs) by the Kerala Girijans and observed that they dedicated approximately 57 per cent of the days in a year to gathering these resources. The revenue earned from selling NTFPs accounted for nearly 58 per cent of the total household income among the tribal communities.

Muraleedharan *et al.* (1999) found that the marketing of NTFPs in Kerala followed different channels based on factors such as product type, demand, and market distance. The products were either sold to private traders, federations, or, in some cases, marketed through the State Forest Department.

Das (2003) studied the collection of sal leaves in West Bengal and noted that women in the household primarily carried out the task. The collection process typically lasted around five hours daily, after which the leaves were brought back to the village. In the evening, all family members, except children, participated in stitching them into plates. On average, an individual could produce between 200 and 250 plates within a four-hour period.

Siribut (2007) examined the socio-economic contributions of agro-biodiversity to the livelihoods of smallholder farmers across three different land-use systems in Chiang Mai province,

northern Thailand. The study found that agroforestry-based systems with collective action exhibited the highest success in fostering strong social relations.

Shukla *et al.* (1990) reported that tribal communities in Danta Taluka, Banaskantha district, generate approximately 33 per cent of their annual household income from forest products. Malhotra *et al.* (1991) found that several village communities in West Medinapore district derive up to 17 per cent of their yearly income through the collection and sale of Non-Timber Forest Products (NTFPs). Similarly, Oberoi *et al.* (1993) analyzed the socio-economic conditions and challenges faced by the tribal economy in Kinnaur district, Himachal Pradesh, revealing that the average annual income of sampled households was ₹18,412.

Nisanth *et al.* (2014) highlighted the socio-economic challenges faced by India's Scheduled Tribes, one of the most marginalized groups. Traditionally reliant on forests for livelihood, industrialization, population growth, and external interventions have forced them to seek alternatives. Limited land, traditional farming methods, and resource scarcity, such as firewood and water, worsened their situation. Industrial expansion and exploitative outsiders further marginalized them, while poverty, illiteracy, and mismanagement of tribal welfare funds deepened their struggles.

Nelson (2007) analyzed recent shifts in agriculture, land use, and livelihoods, highlighting the influence of structural adjustment policies and evolving land tenure systems on agricultural practices. He emphasized that agriculture remains a crucial component of livelihood strategies, particularly for middle- and upper-class residents in peri-urban areas.

Rahimzadeh (2020) examined the decline of *Pinus gerardiana* (chilgoza pine) and its impact on the Kinnaur Tribal Peoples of the Western Himalaya. Based on research from 2010–2018, the study identified factors contributing to reduced chilgoza production, including the shift toward apple cultivation, unsustainable harvesting methods, and climate change, particularly reduced snowfall. The loss of chilgoza threatens economic diversification, increasing Kinnaur Tribal Peoples dependence on a single cash crop. The study highlights the social and environmental consequences of this decline and its broader implications for the region.

Sharma *et al.* (2004) examined the role of non-timber forest products (NTFPs) in the livelihoods of tribal communities in Madhya Pradesh, focusing on three village categories: core, peripheral, and distant villages. The annual cash income generated from selling various NTFPs was found to be ₹12,300 per household in core villages, ₹28,693 in peripheral villages, and ₹39,283 in distant villages. The income increased nearly threefold from core to distant villages.

Giri *et al.* (2005) analyzed NTFP collection in Jharkhand and observed that collectors received only a small portion of the overall market value, while intermediaries benefited the most.

They emphasized the need for policy reforms to ensure better financial returns for local communities. Schwade *et al.* (2006) conducted a study on 313 households across eight villages in Pahang, Peninsular Malaysia, emphasizing the significance of Non-Timber Forest Products (NTFPs) for rural households. Their findings revealed that approximately 65 per cent of collectors in the region sold NTFPs as a source of income. The study also indicated that poorer households or those located farther from markets relied more heavily on NTFP collection for both subsistence and earnings compared to wealthier households. Additionally, the diverse range of NTFPs collected helped mitigate financial risks associated with income generation.

Shylajan and Mythili (2007) reported that tribal communities were legally authorized to collect various NTFPs, with decisions regarding collection, forest range allocation, and pricing managed by the Minor Forest Products (MFP) Committee. Tribal groups established cooperative societies to organize and regulate the collection process. These societies procured NTFPs from gatherers at a price determined by the federation, ensuring that 80 per cent of the sale price was paid to the collectors, while the remaining 20 per cent covered operational expenses. Before the formation of the federation, private traders had monopolized the NTFP trade.

Peltier and Dauffy (2009) observed that over the past decade, many villagers had preferred the contract system for harvesting chilgoza seeds. Their study also highlighted that income from chilgoza contributed between 5 per cent and 25 per cent of a household's total earnings, with the percentage being even higher for economically weaker villagers. It was noted that multiple marketing channels existed for chilgoza nuts, with villagers selling their harvest to itinerant traders, contractors, or directly to consumers at the Lavi fair. The study further revealed that chilgoza seed marketing was seasonal, primarily catering to northern India, where it commanded high prices ranging from £15 to £20 per kilogram.

Piya *et al.* (2011) investigated the collection of Non-Timber Forest Products (NTFPs) by the Chepang community in Nepal and found that households with stable food security and higher alternative incomes relied less on NTFP collection for their livelihood. Further analysis indicated that selling NTFPs was not a highly profitable venture for the community, as the extensive labor required for gathering, cleaning, drying, sorting, and transporting the products was often overlooked when determining market prices. When the cost of family labor was factored in, the actual profit margins for collectors were minimal or nonexistent. Despite this, many continued to engage in NTFP collection due to the limited availability of other income-generating opportunities in the region.

Kar and Jacobson (2012) examined the role of Non-Timber Forest Products (NTFPs) in Bangladesh and found that collecting these resources was deeply linked to the livelihoods of communities living near forests. NTFP collection served both subsistence and income-generating purposes. While these products contributed more to household subsistence than direct cash earnings,

the revenue generated from their sale enabled villagers to purchase essential goods from local markets. However, income levels varied depending on the type of NTFP. Villagers identified bamboo, wild vegetables, broom grass, and sun grass as the most valuable resources for both consumption and trade, as they offered greater market potential compared to others. Despite the high market value of medicinal plants and menda bark, villagers lacked the necessary market knowledge and connections to maximize their earnings from these products. The study also suggested that the economic importance of an NTFP to a household depended on its ability to generate cash income and how extensively it was collected for both personal use and sale.

Aggarwal (2013) highlighted the growing global recognition of NTFPs due to their significant contribution to household economies and food security. Millions of households worldwide relied on NTFPs for both subsistence and steady income.

Melaku *et al.* (2014), in their study in Ethiopia, found that NTFPs played a crucial role in household earnings, with major products like forest coffee, honey, and spices accounting for 47 per cent of annual income. Several factors influenced the role of NTFPs in livelihoods. Forest coffee production was significantly impacted by factors such as being native to the region, land ownership, livestock possession, and access to extension services. Honey production was negatively influenced by the age of the household head and market distance, while positively affected by land ownership. Additionally, household income from NTFPs was determined by factors such as land size (positive impact), and the distance of markets and forests from residences (negative impact). The study emphasized the need for policy development and strategic planning to support household well-being, considering the various factors affecting NTFP collection and utilization.

Thakur *et al.* (2014) conducted research on the drying and storage techniques for chilgoza nuts and determined that using a cabinet dryer set at 55°C was the most effective method for drying. In terms of packaging and storage, the study found that glass jars were the most suitable option, followed by aluminium laminate pouches, for preserving dried nuts under ambient conditions for up to six months. Negi and Subramani (2015) explored the genetic resources of wild edible plants in Kinnaur district, noting that while apples were the primary cash crop, other products such as apricots, almonds, chilgoza nuts, and medicinal plants also held significant market value. Their findings indicated that chilgoza nuts were the most dominant among wild edibles, accounting for over 90 per cent of the total wild edible produce and serving as a key source of income for the region.

Masood *et al.* (2016) studied the socio-economic impact of *Pinus gerardiana* (Chilgoza) in Paddar block, Kishtwar district, Jammu and Kashmir. Surveying 32 villages, they found that Chilgoza nut collection contributed significantly (43.56%) to household income, with Affani village earning the highest (64.88%). However, challenges such as unscientific nut storage (reported by 86.25% of farmers) and damage from unskilled labor (66.25%) affected quality and returns. The study

emphasized the need for technical training in storage and extraction methods to enhance economic benefits for farmers.

2.5 Advances in Molecular Research

Kant *et al.* (2005) conducted a RAPD analysis to evaluate the genetic diversity of *Pinus gerardiana* in Himachal Pradesh. Twenty-four genotypes, randomly sampled from different locations within the species' distribution range, were analyzed. Using 30 random primers, 413 DNA fragments were generated, of which 390 (94%) were polymorphic. Unique bands specific to 11 of the 24 genotypes allowed their individual identification. The similarity coefficient values suggested a broad genetic base among the studied genotypes. An UPGMA dendrogram based on similarity coefficient indices showed that genotypes did not cluster according to their collection sites, likely due to the species' highly cross-pollinating nature and limited distribution in the region.

Moosavi *et al.* (2022) conducted the first genetic analysis of *Pinus gerardiana* (Chilgoza pine) in Afghanistan using microsatellite markers. Eight polymorphic EST-SSRs were used to genotype 191 trees in Gardiz, evaluating genetic diversity, spatial genetic structure (SGS), and population history. The results showed moderate genetic variation, with young trees exhibiting lower heterozygosity and stronger SGS than old trees. While no recent population decline was detected, evidence of an ancient bottleneck event was found. These findings emphasize the need for conservation efforts to preserve the species' genetic diversity and long-term adaptability.

Srivastava *et al.* (2012) conducted a study to examine the genetic relationships among four *Pinus* species using RAPD markers. Five selected primers amplified 500 DNA fragments (234–1353 bp), averaging 8 bands per primer. Cluster analysis revealed one major cluster and one outlier, with *Pinus roxburghii*, *P. wallichiana*, *P. kesiya*, and *P. gerardiana* forming two subclusters. Similarity coefficients ranged from 0.54 to 0.88, with the highest similarity between *P. wallichiana* and *P. roxburghii* (Malithi) and the lowest between *P. gerardiana* (Raspa) and *P. kesiya* (South Vietnam). The low polymorphism observed indicates a close genetic relationship among the samples.

Gul *et al.* (2021) studied the genetic diversity and morphological variation of *Pinus gerardiana* along an environmental gradient in the Takhte Suleman Mountain Range, Zhob, Balochistan, Pakistan. The research examined the influence of altitude and soil variables on the species' morphology, phytochemicals, and genetic diversity. Twenty-seven genotypes were collected from three elevation zones (2000–3500 m). Genetic diversity was analyzed using RAPD and ISSR markers, generating a UPGMA-based dendrogram. Morphological traits were assessed, and phytochemical analysis measured total phenolic and flavonoid contents. The results showed significant variation along altitudinal gradients, with the highest diversity observed at mid-altitudes.

These findings highlight the role of environmental factors in shaping genetic diversity and support conservation efforts for this economically valuable species.

Ranot and Sharma (2019) studied *Pinus gerardiana* (Chilgoza), a small to medium-sized evergreen tree known for its valuable edible nuts, to assess its isozyme variations. Seven enzyme systems—MDH, GDH, SKDH, 6PGDH, MNR, IDH, and ADH—were analyzed, identifying 16 gene loci. Among them, six loci (MDH-A, 6PGDH-A, SKDH-A, IDH-B, MNR-B, and ADH-A) were polymorphic, while the remaining ten loci showed no variation. The percentage of polymorphic loci and the average number of alleles per locus serve as key indicators for evaluating genetic diversity across populations and species.

Kant and Sharma (2004) studied the genetic variation in *Pinus gerardiana* (Chilgoza pine), a sparsely distributed conifer threatened by excessive cone harvesting, which hampers natural regeneration. The research analyzed ten populations in Himachal Pradesh using isozyme markers. Nine isozyme loci across four enzyme systems were recorded, with 15 alleles identified. The loci PER-I, EST-II, and AAT-II exhibited the highest variability in allele frequency, while PER-II and NADH-I appeared heterozygous. Genetic variation parameters varied among populations, with some isolated populations showing low diversity, possibly due to inbreeding. Similarity coefficients and genetic distances indicated substantial differences among populations, with up to 7 per cent of total variation attributed to population differences—relatively high for conifers. Negative F-statistics suggested that the species is highly heterozygous in nature.

Motieimehr *et al.* (2023) investigated the genetic diversity and structure of *Pinus gerardiana* in Afghanistan using SCoT and iPBS markers. Thirty-nine genotypes from five provinces were analyzed, revealing low genetic diversity and a high level of cross-pollination. Polymorphism was 20.8 per cent for SCoT and 29.1 per cent for iPBS markers, with iPBS showing greater differentiation power. The UPGMA dendrogram showed no clustering by collection site, and AOVA indicated higher genetic variation within populations than among them. STRUCTURE analysis identified two genetic groups with admixture. These findings provide crucial insights for the conservation and sustainable management of this economically significant species.

Khan *et al.* (2021) studied *Pinus gerardiana* (Chilgoza pine), an ecologically and economically important species facing regeneration challenges in the Suleiman Range, Pakistan. Due to low seed germination caused by fungal and bacterial infections, in-vitro cultivation was explored using mature zygotic embryos (MZE) and juvenile cotyledons. Cultures were grown in MS and WP media with varying concentrations of BAP, 2,4-D, and IBA. The highest growth (54%) was observed in WP media at 0.5 mg/l. Cotyledon-derived cultures showed better adventitious bud induction, while MZE proved effective for embryogenic culture development in *P. gerardiana*.

Rawat *et al.* (2013) evaluated genetic variability among 53 *Pinus roxburghii* genotypes from Uttarakhand, India, using 19 SSR, 9 ISSR, and 5 AFLP markers. Resin yield varied from 0.25 to 8 kg/year/tree. SSR markers were the most polymorphic (PIC = 0.327, 2.42 alleles/marker), while ISSR had the highest effective multiplex ratio and marker index. AFLP showed the highest resolving power. UPGMA clustering using SSR markers grouped genotypes more distinctly by resin yield. AMOVA indicated that genetic variation was linked to resin yield (F_{ST} : SSR = 0.1096, ISSR = 0.0483, AFLP = 0.2422) rather than collection site.

Sheikina and Romanov (2024) investigated genetic diversity and differentiation in plus trees of Scots pine using ISSR markers. Six ISSR primers were applied to 270 plus trees from the Penza region, Chuvash Republic, Republic of Tatarstan, and Mari El Republic. A total of 215 PCR fragments were identified, with genetic variability ranging from 95.7–96.9 per cent polymorphic loci and expected heterozygosity between 0.205–0.298. ANOVA showed that 82 per cent of genetic variability existed within plus tree samples, while 18 per cent was among geographic groups. UPGMA clustering revealed similarity among most regions, except Mari El, which formed a distinct group.

Mei *et al.* (2021) studied the genetic diversity and population structure of Masson pine (*Pinus massoniana*) in three seed orchards in South China using 24 EST-SSR markers. All loci were polymorphic, with an average of six alleles per locus and 168 rare alleles. The mean polymorphism information content (PIC) was 0.7011, indicating high marker informativeness. Most genetic variation was within populations, with moderate differentiation among them. STRUCTURE, UPGMA, and PCoA analyses identified three clusters, though they were not strictly based on geography or traits. These findings support the conservation and management of Masson pine germplasm.

Masternak *et al.* (2018) analyzed the genetic variability of Pitch pine (*Pinus rigida*) in the Niepołomice Forest, southern Poland. Using ISSR markers, they examined 227 trees across seven subunits. The study found a high level of genetic variability, with an average of 1.649 alleles per locus, an effective allele counts of 1.435, and 75.30 per cent polymorphic loci. Expected heterozygosity was 0.254, and the average genetic distance was 0.082. PCoA and STRUCTURE analyses identified three genetic groups, mainly differentiated by the SR70 primer. The findings suggest different seed origins for the experimental plots.

Chapter - 3

MATERIALS AND METHODS

The study, titled “**Population Dynamics and Stand Structure of *Pinus gerardiana* Wall. in the Dry Temperate Forests of Himachal Pradesh,**” was carried out across four sites in Kinnaur and one in Chamba. This chapter outlines the research approach, detailing the study area's characteristics, materials used, and methodologies employed. It highlights the research design, data collection techniques, sampling methods, and procedures used to derive key conclusions.

3.1 EXPERIMENTAL SITE

3.1.1 Location

Research on morphological variation, stand structure, phytosociology, natural regeneration status, soil nutrient dynamics, socioeconomic conditions, and molecular analysis was conducted in Chilgoza forests across four ranges Kalpa, Kilba, Moorang, and Pooh in Kinnaur district and Pangi in Chamba. These sites encompass the entire distribution range of the species (Fig.1). The Table-1 below presents the study site and selected genotypes, along with elevation and coordinates.

Table: 1 Details of the genotypes of *Pinus gerardiana* under study

Population	Mean elevation (m)	Genotypes	Latitude (°N)	Longitude (°E)
Kalpa	2765	KLP1 (T1)	31.53753	78.25559
		KLP2 (T2)	31.53073	78.26866
		KLP3 (T3)	31.53037	78.26688
		KLP4 (T4)	31.53147	78.26668
		KLP5 (T5)	31.54068	78.25158
Kilba	2310	KBA1 (T6)	31.51291	78.15501
		KBA2 (T7)	31.51296	78.15606
		KBA3 (T8)	31.51282	78.15668
		KBA4 (T9)	31.51376	78.15419
		KBA5 (T10)	31.51225	78.15817
Moorang	2850	MRG1 (T11)	31.58903	78.38268
		MRG2 (T12)	31.5887	78.38342
		MRG3 (T13)	31.58821	78.38139
		MRG4 (T14)	31.58819	78.3815
		MRG5 (T15)	31.58938	78.38068

Pooh	2970	POO1 (T16)	31.78588	78.43745
		POO2 (T17)	31.78542	78.43679
		POO3 (T18)	31.78552	78.43727
		POO4 (T19)	31.78562	78.43652
		POO5 (T20)	31.78597	78.43577
Pangi	2356	PNG1 (T21)	33.12522	76.35637
		PNG2 (T22)	33.12536	76.35652
		PNG3 (T23)	33.12436	76.35617
		PNG4 (T24)	33.12368	76.35652
		PNG5 (T25)	33.12496	76.35615

3.2 EXPERIMENTAL METHODOLOGY

3.2.1 Experiment 1: To study the morphological variation and stand characteristics of chilgoza pine.

The details of the materials and methods used for assessing morphological variation in the experimental field, laboratory, and statistical analysis are outlined below.

The study sites were selected based on the presence of *Pinus gerardiana* trees/stands suitable for research. The selected sites included Kalpa, Kilba, Moorang, and Pooh ranges in Kinnaur, as well as the Pangi Range in Chamba. From each site, five genotypes were chosen, total 25 genotypes for the morphological variation study.

3.2.1 Observations recorded:

3.2.1.1 Growth traits:

The following growth traits were observed in different *Pinus gerardiana* genotypes and were measured using standard procedures:

1) Height:

It was measured by Ravi altimeter in meter (m).

2) Diameter:

It was measured at breast height (1.37 m) in centimetres (DBH) by using tree calliper.

3) Crown width

The crown width was measured in two directions (North-south and East-west) and average was calculated as suggested by Assmann (1970) and Chaturvedi and Khanna (1982)

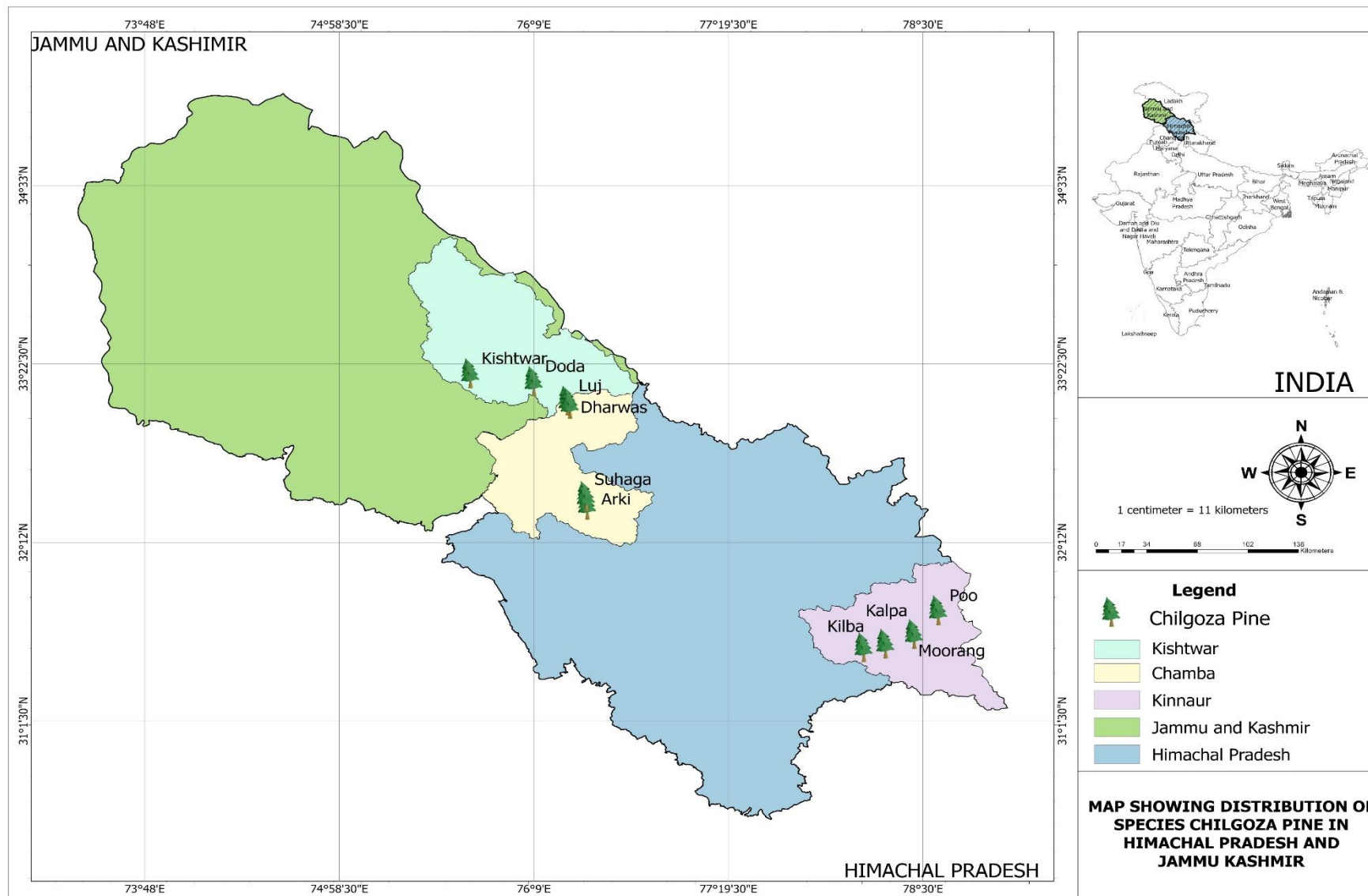


Fig. 1. Map showing the distribution of Chilgoza pine in India

$$CW = \frac{D1 + D2}{2}$$

Where:

CW – Crown width (m)

D1 – First measured crown diameter (m)

D2 – Second measured crown diameter at right angle to the first Measurement (m)

4) Crown projection ratio

It is the ratio which states that by how many times the crown diameter is larger than the stem diameter (Assmann, 1970).

Crown project ratio = b/d

Where: b - Crown width

d - Stem diameter

5) Solar influx

Light illumination was recorded by luxmeter under and outside the chilgoza pine canopy in selected forest sites / elevations separately during day time. The value in percentage of light intensity under canopy to that in the open was calculated as under (Rao, 1998).

$$\text{Solar influx (\%)} = \frac{\text{Total solar radiation beneath the canopy}}{\text{Total solar radiation in open}} \times 100$$

3.2.1.2 Needle, cone and seed characteristics

1) Needle Length

The average length of these needles was measured with the help of simple scale and expressed in centimetres.

2) Cone length

The average length of these cone was measured with the help of simple scale and expressed in centimetres.

3) Cone width

The average width of these cone was measured with the help of simple scale and expressed in centimetres.

4) Seed length

The average length of these seed was measured with the help of simple scale and expressed in millimetres.

5) Seed width

The average width of these seed was measured with the help of simple scale and expressed in millimetres.

6) 100 seed weight

The average weight of these 100 seed was measured with the help of electronic balance and expressed in grams.

3.2.1.3 Estimation of stand characteristics

3.2.1.4 Identification of main species and its associates

All the trees falling under each sample plot were identified before going for further estimations.

3.2.1.5 Individual tree measurement

Trees falling in each sample plot were enumerated to determine the stand density as number of plants per hectare.

Tree height:

It was measured by Ravi altimeter in meter (m).

Diameter:

It was measured at breast height (1.37 m) in centimetres (DBH) by tree calliper.

Crown width

The crown width was measured in two directions (North-south and East-west) and average was calculated as suggested by Assmann (1970) and Chaturvedi and Khanna (1982)

$$CW = \frac{D1 + D2}{2}$$

Where:

CW – Crown width (m)

D1 – First measured crown diameter (m)

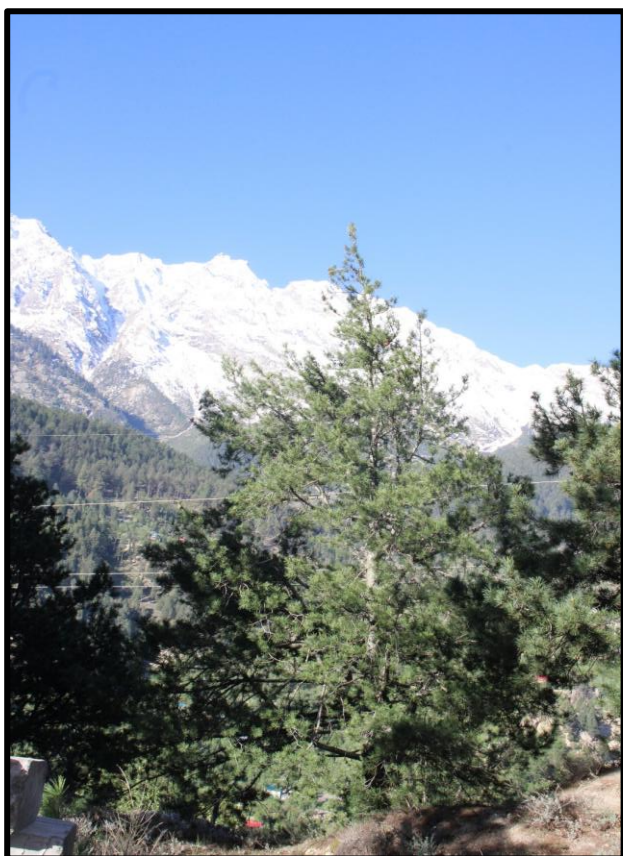
D2 – Second measured crown diameter at right angle to the first Measurement (m)



KALPA



KILBA



MOORANG



POOH



PANGI

Plate 1. Representative mother trees of *Pinus gerardiana* from different populations

Crown projection ratio

It is the ratio which states that by how many times the crown diameter is larger than the stem diameter (Assmann, 1970).

Crown project ratio = b/d

Where: b - Crown width

d - Stem diameter

3.3. Experiment 2: To study the phytosociology of chilgoza pine in dry temperate forest of Himachal Pradesh.

3.3.1 Community analysis

The study on phytosociology and floristic composition in chilgoza pine bearing forests was carried out after laying out the sample plots in each of the selected range. The quadrats (31.62 m×31.62 m (FSI, 2015) was laid out in all the natural populations to study the associations of tree species in vicinity of *Pinus gerardiana* using the species area curve method (Arrhenius, 1921; Testolin *et al.* 2024; Yang *et al.* 2024). In each quadrat, further five sub-quadrats were laid out for shrubs (10m × 10m) and ten sub quadrats for herbs (1 m×1 m), respectively (Albrecht *et al.* 2024).

3.3.2 Trees

In each natural population, a sample plot of approximately 0.1 ha (31.62 m×31.62 m) or the most suitable quadrat size, depending on the forest area, was established to enumerate tree species associated with *Pinus gerardiana*. (Duffy *et al.* 2024).

In each sample plot the trees of different species were counted, averaged and density of each tree species was evaluated. The height of trees was computed by Ravi multimeter, and diameter at breast height (DBH) with Vernier caliper (Das *et al.* 2019)

3.3.3 Shrubs

In every sample plot of 0.1 ha, three sub plots of 5 m×5 m, was laid out for studying the phytosociology of shrubs. On the basis of visual appearance each shrubs species was segregated into three groups as: large, medium and small. Proportionate sampling method was applied to sample shrub plants from each group to determine the basal area of stem. The number of numerous shrubs in each plot were counted and basal area of each shrub was determined from the base using vernier caliper (Yuan *et al.* 2024).

Basal area of shrub = $\pi d^2/4$

Where, d = diameter of the main stem

3.3.4 Herbs

Two line transects were laid out across each natural population and ten sub-quadrats of size 10 cm × 10 cm were randomly selected to study the diversity of herbs, at the time of peak growth of herbage in the month of September (Sun *et al.* 2024). The herbage each quadrat was segregated into grass, sedge, legume and forb and, further into their species.

The identification of plants was done with the help of experts in the university herbarium in the Department of Forest Products, Dr. YSP University of Horticulture & Forestry, Solan (HP) and from 'Systematic Botany' division in HFRI, Panthaghati, Shimla.

The vegetation data were quantitatively analyzed for density, percent frequency and abundance. Relative Frequency, Relative Density and Relative Basal Area were determined following Phillips (1959).

Percent Frequency: It expresses the distribution of various species in a community. The percent frequency was calculated as follows:

$$\text{Percent frequency} = \frac{\text{Number of sampling units in which this species occurs}}{\text{Total number of units studied}} \times 100$$

Density: The term density denotes the numerical strength of species in the community. It was calculated as follows:

$$\text{Density} = \frac{\text{Total no. of individuals}}{\text{Total no. of quadrates studied}}$$

Mean basal area: It refers to the area covered by stems (Hanson and Churchill, 1961) and calculated by using following relation.

$$\text{Basal area} = \pi d^2/4$$

Where d = diameter

For shrubs and herbs, the diameter was measured with the help of digital vernier caliper. Relative dominance, Relative density and Relative frequency were calculated from the per cent frequency, density and basal area formula given by Phillips (1959).

$$\text{Relative dominance} = \frac{\text{Total basal area of the species}}{\text{Total basal area of all species}} \times 100$$

$$\text{Relative density} = \frac{\text{Number of individuals of the species}}{\text{No. of individuals of all species}} \times 100$$

$$\text{Relative frequency} = \frac{\text{No. of occurrence of the species}}{\text{No. of occurrence of all species}} \times 100$$

Importance Value Index (IVI):

The Importance Value Index (IVI) expresses the dominance and success of any species in a community. IVI is a sum of relative frequency, relative density and relative dominance. It was calculated for all the shrubs and herbs species individually in different sites.

$$\text{IVI} = \text{Relative dominance} + \text{Relative density} + \text{Relative frequency}$$

3.3.5 Similarity and dissimilarity indices

These indices were calculated using formulae as given by Mishra (1969)

$$\text{Index of similarity (S)} = 2C / A+B$$

Where,

A=Number of species in community A

B= Number of species in community B

C= Number of species common in both the communities

$$\text{Index of dissimilarity} = 1-S$$

3.3.6 Vegetation indices

3.3.7 Species richness (D_{mg})

The Species Richness was calculated by using the method 'Margalef's index of richness' (D_{mg}) (Magurran, 1988).

$$D_{mg} = S-1 / \ln N$$

Where,

D_{mg} = Margalef's index of richness

S = Total number of species.

N= Total number of individuals.

3.3.8 Shannon-Wiener (1963) Index of diversity (H)

It was calculated by using the given formula:

$$H = -\sum p_i \ln p_i$$

Where,

H = Shannon Index of diversity

p_i = the proportion of important value of the i^{th} species ($p_i = n_i/N$, n_i is the importance value index of i^{th} species and N is the important value index of all the species).

3.3.9 Simpson (1949) index of dominance (D)

The Simpson's index was calculated by the given equation:

$$D = \sum (p_i)^2$$

$$p_i = n_i/N$$

Where,

D = Simpson index of dominance.

p_i = the proportion of important value of the i^{th} species,

n_i = the important value index of i^{th} species

N = the important value index of all the species.

3.3.4.1 Equitability (e)

The Equitability was calculated by following method:

$$e = H/\ln S$$

Where,

e is equitability

H is Shannon-Weiner Index and S is Total number of species

Experiment 3: To study the natural regeneration status and soil nutrient dynamics in different chilgoza pine forests

3.4.1 Natural regeneration status

Within each demarcated sample plot of 31.64×31.64 m, the regeneration survey was carried out in a square plot of size 2×2 m by recording the number of seedlings (<0.5 m) and sapling (0.5-2 m) of tree species. The main object of regeneration survey is to assess whether or not there is adequate regeneration in the forest area. The adequacy of regeneration is

judged on the basis of number of established plants in a unit area. According to Chacko (1965), the desired numbers of established plants are 2500 number ha⁻¹ and the quadrat is considered fully stocked when it contained one established plant. For a detailed assessment of the status of regeneration following observations were made for each quadrat.

Recruits, un-established, established and per cent regeneration

- I. The total number of recruits (r) - which may be defined as current year seedlings.
- II. The number of un-established regeneration (u) - Seedling other than recruits which has not established by not reaching established height of 2 m. Four un-established plants were considered equivalent to one established plant and,
- III. The number of established regeneration (e) - Seedlings above 2 m height.

The recruits, un-established and established regeneration were computed using formulae given by Chacko (1965) as:

$$\text{Recruits (r)/ha} = \frac{2500 \times \text{Total number of individuals}}{\text{Total number of quadrates studied}}$$

$$\text{Unestablished regereation (u)/ha} = \frac{2500 \times \text{total number of unestablished plants in sampling units}}{\text{Total number of recording units}}$$

$$\text{Established regereation (e)/ha} = \frac{2500 \times \text{total number of established plants in sampling units}}{\text{Total number of recording units}}$$

$$\text{Weighted average height (cm)} = \frac{\text{Total ht. of unestablished regeneration} + (\text{Number of established plants} \times \text{establishment ht.})}{\text{Total unestablished plants} + \text{Total established plants}}$$

On the basis of above estimates following indices were calculated:

$$\text{Established index (I}_1\text{)} = \frac{\text{Weight average height}}{\text{Established height}}$$

$$\text{Stocking Index (I}_2\text{)} = \frac{1}{2500} \times \frac{\text{unestablished regeneration}}{4} + \text{Established regeneration}$$

Regeneration success (%) = Stocking Index (I_2) $\times$ 100

Established stocking per cent = 100 ($I_1 \times I_2$)

3.4.2 Soil Analysis

3.4.3 Collection of soil samples

The composite soil samples at three depths (0-20, 20-40, 40-60 cm) from each sample plot under the different natural populations of *Pinus gerardiana* were collected during autumn season, in three replicates of each composite sample (Dasila *et al.* 2024). These soil samples were packed in cloth bags, marked and brought to the main campus, air dried, made free from plant material and gravels, etc., passed through a sieve of 2 mm mesh and again stored in cloth bags separately (Ande *et al.* 2021).

3.4.4 Soil pH

The air-dried soil samples were dissolved in double distilled water (1:2), shaken on electric shaker for two hours, allowed to rest and pH estimated through digital pH meter (Jackson, 1973).

3.4.5 Electrical conductivity (EC)

EC was estimated from the supernatant liquid of the same samples used for pH estimation using conductivity bridge (Jackson, 1973).

3.4.6 Organic carbon (OC)

Weighted out 2 g of soil in a 250 ml conical flask. Added to it, 10 ml of 1N $K_2Cr_2O_7$ solution and mixed. Then added 20 ml of concentrated H_2SO_4 , while swirling the flask during addition. Left the flask as such so as to cool the contents and make the reaction complete. Then added approximately 2 g of NaF powder or 10 ml of orthophosphoric acid, (both NaF and orthophosphoric acid are the flocculation agents) 100 ml of distilled water and shake vigorously. Added 10 drops of diphenylamine indicator, which gave a violet colour to the suspension. Titrated the contents of the flask with 0.5 N ferrous ammonium sulphate solution. The end point in this titration was a change of the colour from blue violet to bright green. Noted the volume of the ferrous ammonium sulphate solution used and calculate the results. Run a blank titration also in the similar way (Walkley and Black, 1954; Babej *et al.* 2024).

3.4.7 Nitrogen (N)

Available nitrogen was determined through Macro Kjeldahl method (Subbiah and Asija, 1956; Bin *et al.* 2024). Air dried soil (1 g) was digested with sulphuric acid, ammonia evolved absorbed in boric acid and titrated against standard hydrochloric acid and amount of nitrogen calculated accordingly.

3.4.8 Phosphorus (P)

Available phosphorus was extracted by sodium bicarbonate method and determined through colorimetric method following Olsen *et al.* 1954 and the blue colour developed was read at 660 nm within 20 minutes on Spectronic-20 against a blank (Onyinye *et al.* 2024). The amount of available phosphorus was calculated from the standard curve prepared from KH_2PO_4 .

3.4.9 Potassium (K)

The quantitative estimations of potassium, sodium and calcium were carried through ammonium acetate extract following Mesele *et al.* (2024). The leachates were diluted to desired amount and treated as stock solution. The estimations were carried out through Flame Photometer against their respective filters. Standards for K, Na and Ca were prepared from KCl, NaCl and CaCO_3 , respectively

Experiment 4: To study of the socio-economic status of the chilgoza nut collectors

3.5.1 For proposed study both primary data and secondary data will be used

For the present study, five sites were selected, including four locations from Kinnaur district (Kalpa, Kilba, Moorang, and Pooh) and one site from Chamba district (Pangi). A simple random technique was used to select the 12 respondents from each site, resulting in a total sample size of 60 respondents.

3.5.2 NATURE AND SOURCES OF DATA

To achieve the objectives of the present study, both primary as well as secondary data were collected

Primary data

Primary data were gathered using well-structured and pre-tested schedules through personal interviews with selected households and traders/intermediaries. The collected

information covered various demographic aspects, including family size, age, and education, along with socio-economic parameters such as land use, livestock holdings, cropping patterns, and income sources.

Secondary data

The secondary information pertaining to the list of panchayats, CPRs etc were collected from Govt. offices, Forest Department, as well as from the various available literatures and websites.

3.5.3 Analytical tools and techniques employed

Analytical tools and techniques are required to deduce meaningful information from the obtained data. To achieve the specific objectives of the study, the following analytical tools and techniques have been adopted.

- Tabular analysis

3.5.4 Socio economic status

A simple tabular approach was utilized to assess the socio-economic conditions, income levels, and expenditure patterns.

Table: 2 Distribution of surveyed households based on landholding size.

Category of farmers	Size of land holding (ha ⁻¹)	No. of farmers	Percentage offarmers	Average size of holding (ha ⁻¹)
Marginal	<1	28	46.67	0.58
Small	1-2	20	33.33	1.38
Medium	>2	12	20.00	3.05
Total		60	100.00	1.43

For data analysis, the total respondents were categorized into three groups based on their landholding size: marginal (<1 ha), small (1-2 ha), and medium (>2 ha). The distribution of sampled Chilgoza collectors according to landholding size is presented in the table above. The results indicate that 46.67 per cent of the respondents belonged to the marginal category, 33.33 per cent were classified as small farmers, and 20.00 per cent fell into the medium category. The average landholding size across all respondents was 1.43 ha⁻¹, with variations ranging from 0.58 ha⁻¹ among marginal farmers to 3.05 ha⁻¹ in the medium category.

Basic statistical methods, including averages and percentages, were employed for comparison and interpretation of results. Additionally, the following indices were calculated for this study:

$$\text{Literacy Rate (\%)} = \frac{\text{Total no. of literate persons}}{\text{Total Population} - \text{Population below 5 years}} \times 100$$

$$\text{Literacy Index} = \frac{\sum W_i X_i}{\sum X_i}$$

Where;

W_i = Weights (0,1,2,3,4,5 and 6) for illiterate, primary, middle, matric, intermediate, graduate, postgraduate and above respectively.

X_i = Number of persons in respective category.

$$\text{Dependency Ratio with respect to total workers} = \frac{\text{No. of dependents in a family}}{\text{Total workers}}$$

$$\text{Dependency Ratio with respect to average family size} = \frac{\text{No. of dependents in a family}}{\text{Average size of family}}$$

$$\text{Cropping intensity} = \frac{\text{Gross cropped area}}{\text{Net sown area}}$$

3.5.5 Livestock Inventory

The Adult Cattle Unit (ACU) was worked out by using the conversion factors given by Anonymous (2012c) as follows:

- i) One sheep, goat and calf equivalent to 0.68 ACU.
- ii). One local cow equivalent to 0.74 ACU

3.5.6 Statistical Analysis

The execution of comprehensive statistical analyses was an integral part of this study, aimed at extracting valuable insights from the dataset. To achieve this, a suite of software tools was strategically employed. These tools, namely IBM SPSS Statistics software (IBM Corp., 2021), Microsoft Excel and R software, collectively facilitated an exhaustive exploration of the dataset. The data obtained for natural variation were subjected to statistical analysis using RBD design. The statistical analysis for each parameter was carried out on mean values and the analysis of variance (ANOVA) table was set up as under:

Variability and genetic parameters

$$PCV (\%) = \frac{\sqrt{V_p}}{\bar{X}} \times 100; V_p = \text{Phenotypic variance}$$

$$GCV (\%) = \frac{\sqrt{V_g}}{\bar{X}} \times 100; V_g = \text{Genotypic variance}$$

$$ECV (\%) = \frac{\sqrt{V_e}}{\bar{X}} \times 100; V_e = \text{Environmental variance}$$

Where, PCV = Phenotypic Coefficient of Variability GCV = Genotypic Coefficient of Variability ECV = Environmental Coefficient of Variability X = Population mean of character

$$CV (\%) = \left(\frac{SD}{\bar{X}} \right) \times 100$$

Where, SD = Standard deviation X = Population mean

Heritability (Broad sense)

$$h_{b.s}^2 = \frac{V_g}{V_p} \times 100$$

Genetic Advance

$$GA = \left[\frac{V_g}{V_p} \right] \times (\sqrt{V_p}) \times K$$

Where, K = Selection differential at 5 per cent selection intensity

Genetic gain

$$\text{Genetic Gain (\%)} = \frac{GA}{\bar{X}} \times 100$$

Correlation analysis

$$r(XY) = \frac{\text{Cov.}XY}{\sqrt{V(X) \cdot V(Y)}}$$

Where, r (XY) = Simple correlation Between X and Y V (X) = Variance of X character V (Y) = Variance of Y character. The significance of r values were tested against (n-2) degree of freedom by using Fisher and Yates tables.

3.5.7 Principal Component Analysis (PCA)

Principal component analysis or canonical (vector) analysis was carried out to study the amount of variation along different axis of differentiation. It is a multivariate statistical technique to reduce the data with large number of correlated variables into a substantially smaller set of new variables, through linear combinations of variables that account most the

variation presents in the original variables. PCA is a function of Eigen values and Eigen vectors covariance matrix. The factors having Eigen values less than one were not taken for further consideration. Since the aim of principal component analysis is to replace the original set of variables with few variables as possible, so some information contained in the original variables has to be sacrificed, but this lost information is minimum (Kaiser (1958).

Genetic divergence was estimated by Mahalanobis D^2 Statistics and the half sib families were grouped on the basis of minimum generalized distances using Tocher's method as described by Pearson (1901). Using SPSS.16 software, which grouped the diverse families into different clusters, based on the mean of the growth traits, needle characteristics and wood traits.

3.5.8 Cluster analysis of phenotypic data

Furthermore, a hierarchical cluster analysis was performed to see whether genotypes of similar origin or parentage clustered together and to visualize the multivariate effects characterizing biomass production. Cluster analysis is an appropriate tool for evaluating and classifying genotypes according their productivity and related traits (Tharakan *et al.* 2005). Ward's method of clustering with interval of the squared Euclidean distance was used as measure for similarity; complete linkage (furthest neighbour) was applied as clustering algorithm (Johnson and Wichern, 2002).

For the hierarchical clustering analysis, the R software (R Core Team, 2021) was employed. The stats package (included in the base R distribution) was used to perform the hierarchical clustering using Ward's linkage method. Silhouette scores were calculated using the 'cluster' package (Maechler *et al.* 2021) in R to evaluate the quality of the clustering results.

Experiment 5: To assess the genetic diversity of chilgoza pine genotype using DNA based molecular markers.

3.6.1 DNA isolation and purification

3.6.2 Plant materials

The needles of *Pinus gerardiana* were collected from five distinct sites, delineated by natural features such as streams and mountainous formations. These sites represent the entire distribution range of chilgoza pine in Himachal Pradesh. From each site, the best genotype was selected based on phenotypic characteristics. In total, 25 genotypes—five from each site—were chosen for ISSR analysis. These genotypes, designated as Klp-1, Klp-2, Klp-3,

Klp-4, Klp-5, Klb-1, Klb-2, Klb-3, Klb-4, Klb-5, Mrg-1, Mrg-2, Mrg-3, Mrg-4, Mrg-5, Poo-1, Poo-2, Poo-3, Poo-4, Poo-5, Png-1, Png-2, Png-3, Png-4, and Png-5, were named after their respective collection sites. These genotypes were then selected for further molecular analysis, which was conducted at the Molecular Laboratory of Tree Improvement and Genetic Resources, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh.

3.6.3 DNA isolation

The genomic DNA isolation was carried out by CTAB method (Doyle and Doyle 1987) with slight modifications. The DNA was isolated from the needles of each genotype. First, 100 mg of fresh needles were weighed and placed in a mortar. The needles were ground in the mortar with liquid nitrogen, and the lyophilized ground tissue was transferred to a 2 ml tube. Next, 1 ml of CTAB buffer was added to the tube, followed by 2 μ L of RNase A. The mixture was gently inverted to mix and incubated at 65°C for 1 hour. After incubation, the tubes were cooled for 5–10 minutes at room temperature. Then, 1 ml of phenol-chloroform-isoamyl alcohol was added to each tube, and the mixture was shaken manually to form an emulsion. The tubes were centrifuged at maximum speed (13,000–15,000 rpm) for 8–10 minutes. Following centrifugation, three distinct layers were observed: the top layer (aqueous phase containing DNA), the middle layer (debris and proteins), and the bottom layer (chloroform). The aqueous phase (top layer) was carefully pipetted off into labelled 1.5 ml tubes, ensuring no contamination from the middle or bottom layers. An equal volume of cold isopropanol (2-propanol) was added to the aqueous phase, and the mixture was inverted to mix. The samples were then left in a freezer at -20°C for 45 minutes to 1 hour. It was noted that longer incubation times (e.g., overnight) yielded more DNA but increased the presence of contaminants. After freezing, the samples were centrifuged at maximum speed for 5 minutes at 4°C. The liquid was carefully removed, ensuring the DNA pellet, which was loose and difficult to see, was not disturbed. The pellet was washed by adding 700 μ l of cold 70% ethanol and 20 μ l of ammonium acetate, followed by gentle inversion. The samples were centrifuged again at maximum speed for 1 minute. The liquid was removed, and the pellet was washed a second time with 700 μ l of cold 95% ethanol, followed by gentle inversion. The samples were centrifuged again at maximum speed for 1 minute. The liquid was carefully removed, and the pellet was allowed to dry. Finally, the DNA pellet was resuspended in 100 μ l of TE buffer (or ddH₂O), and the samples were stored at 4°C for further use.

3.6.4 Reagents

The solutions required for isolation and purification of DNA were prepared as follows:

(A) Preparation of Stock solutions (500 ml) for DNA extraction

a) 0.5 M EDTA: 93.05 g

b) 1M Tris-Cl: 60.55 g

c) 5 M NaCl: 146.1 g

The pH of 0.5 M EDTA and 1 M Tris-Cl was adjusted to 8.0. The solution was autoclaved after making the final volume upto 500 ml.

d) CTAB Buffer

CTAB (2%): 10 g 0.5M EDTA: 20 ml

1 M Tris-Cl: 50 ml

M NaCl: 140 ml

ddH₂O:

β- mercaptoethanol : 0.2%

The final volume of CTAB buffer was made up to 500 ml using double distilled H₂O. It was then autoclaved after adjusting the pH to 8.0. β-mercaptoethanol (0.2%) was added immediately before use.

e) TE Buffer (10 X)

1 M Tris-Cl: 100 ml

0.5 M EDTA: 20 ml

880 ml ddH₂O was added to make 1L TE Buffer. pH was adjusted to 8.0 and autoclaved.

f) RNase (10mg/ml) – 10ml

5 M NaCl: 30 μl

1 M Tris-Cl: 100 μl

ddH₂O: 987 μl

RNase: 10mg

The solution was boiled for 15 minutes, allowed to cool at room temperature and stored at 4°C.

3.6.5 DNA Quantification

Quality and quantity of genomic DNA was estimated by using Agarose gel electrophoresis and Nanodrop method. Quantity of DNA was checked by spectrophotometer by measuring absorbance from 230 nm to 320 nm to detect other possible contaminants

Agarose Gel Electrophoresis: Before proceeding for gel electrophoresis, stock solutions to be used for electrophoresis were prepared as follows

a) Preparation of Buffers

1. TBE Buffer (10 X) for 1L

Tris Base: 108 g

Boric acid: 55 g

0.5 M EDTA (pH 8): 40 ml

Double distilled water was used to make the final volume upto 1L, mixed with the help of magnetic stirrer and autoclaved.

2. Tank Buffer (1X TBE)

100 ml 10X TBE was dissolved in 900 ml double distilled water to make 1L of 1 X TBE

3.6.6 DNA Loading Dye (6X)

Glycerol: 30 % (v/v)

Bromophenol Blue : 0.25 % (w/v)

Xylene cyanol : 0.25 % (w/v)

DNA was quantified by loading 2 µl of DNA mixed with 6 µl of loading dye (ready to use) into separate wells on 1 per cent agarose gel. It was prepared by melting 1 g agarose in 100ml 1X TBE (Tris, Borate, EDTA) buffer in a microwave for 2 minutes. It was allowed to cool for a couple of minutes and then stained with ethidium bromide and stirred for some time. It was then poured in the casting tray with 26 combs in it and allowed to solidify for 20-

25 minutes at room temperature. DNA concentration standards were also loaded to estimate the concentration of DNA in each sample. The electrophoresis was carried out at 75V for 2 hours. It was then viewed under gel documentation system. The concentration of DNA was determined by comparing the intensity of bands with that of standards.

3.6.7 INTER SIMPLE SEQUENCE REPEAT (ISSR) STUDIES

3.6.8 Primer used for DNA amplification

A total number of 15 ISSR primers were used to evaluate genetic diversity of 25 *Pinus gerardiana* genotypes (on the basis of seedling characteristics 2 phenotypically superior trees were selected from each population) (Table 3).

Table 3. Details of ISSR primers

Sr. No.	Primer Id	Marker sequence (5'-3')
1.	UBC-807	AGAGAGAGAGAGAGAGT
2	UBC-808	AGAGAGAGAGAGAGAGC
3	UBC-809	AGAGAGAGAGAGAGAGG
4	UBC-811	GAGAGAGAGAGAGAGAC
5	UBC-818	CACACACACACACACAG
6	UBC-823	TCTCTCTCTCTCTCC
7	UBC-825	ACACACACACACACT
8	UBC-829	TGTGTGTGTGTGTGTC
9	UBC-834	AGAGAGAGAGAGAGAGGT
10	UBC-835	AGAGAGAGAGAGAGAGCC
11	UBC-840	GAGAGAGAGAGAGAGAAT
12	UBC-842	GAGAGAGAGAGAGAGAGG
13	UBC-861	ACCACCACCACCACCACC
14.	nISSR-1	CAGCAGCAGCAGCAG
15.	nISSR-2	CAACAACAACAACAA

Table 3. Details of 15 ISSR primers used for the diversity analysis

3.6.9 PCR amplification

A total of fifteen ISSR primers were used, amongst them all were polymorphic. The amplification reactions were carried out in a final reaction volume of 20 µL. The PCR

mixture consisted of 3 mM MgCl₂, 1X PCR buffer, 0.2 mM dNTPs, 20 pmol primers, 0.01% gelatin, 1 U/rxn DreamTaq DNA polymerase, and 25 ng of DNA template. PCR amplification was performed using a thermal cycler (Applied Biosystems, 96-well, USA). The conditions for RAPD primers included an initial denaturation step at 94°C for 3 minutes, followed by 36 cycles of denaturation at 94°C for 1 minute, annealing at 36°C for 1 minute, and extension at 72°C for 2 minutes. A final extension step at 72°C for 5 minutes was included. For URP primers, the PCR conditions consisted of an initial denaturation at 94°C for 3 minutes, followed by 40 cycles of denaturation at 94°C for 1 minute, annealing at 50–56°C for 1 minute, and extension at 72°C for 2 minutes. Similarly, for ISSR primers, the PCR protocol involved an initial denaturation at 94°C for 3 minutes, followed by 40 cycles of denaturation at 94°C for 1 minute, annealing at 56°C for 1 minute, and extension at 72°C for 2 minutes, with a final extension step at 72°C for 5 minutes.

The amplified products were analysed by electrophoresis on 1.8% agarose gels containing 0.5 µg/mL ethidium bromide in 1X TAE buffer. Visualization was performed using a gel documentation system under UV light. The sizes of the amplified products were determined by comparison with a standard DNA ladder (100 bp, BIORON, 0.2 mg/mL).

3.7 Analysis of ISSR Fingerprints

Scoring of allele profile

The allele sizes were determined by the position of bands relative to the DNA ladder. The DNA bands were scored on the basis of relative mobility in gel. The banding patterns of all genotypes against every primer were compared. Data matrices were prepared in which the presence of a band was coded as 1, whereas the absence as 0. The scored bands were analyzed in the form of binary system for ISSR to prepare the similarity index. The allele difference was determined according to their fragment size (bp) corresponding to the 100 bp standard marker (Sigma Aldrich, U.S.A) for ISSR markers. The accessions that did not show any amplification were scored as missing values if amplification was not repeated and as null alleles if the amplification was repeated 2-3 times. If the band appeared in the negative control the whole PCR reaction experiment was repeated.

3.7.1 Data analysis

3.7.2 Polymorphism and primer informativeness

The genetic diversity parameters like per cent polymorphism, total number of bands amplified per primer and number of polymorphic bands were calculated. Genotypic data obtained for different 53 primers was used for assessing the discriminatory power of primers and determining the utility of each primer by evaluating the parameters.

Polymorphism Information Content (PIC) was calculated with different formulas (Chesnokov and Artemyeva, 2015). Effective multiplex ratio, Marker index (MI) (Powell *et al.* 1996) and Resolving Power (Chesnokov and Artemyeva, 2015) of primers were calculated.

3.7.3 Polymorphism information content (PIC)

Average PIC indicates the ability of utilized markers to differentiate the genotypes: It was calculated according to the following formula given by Anderson *et al.* (1993). $PIC = 1 - \sum_{j=1}^n (p_{ij})^2$ Where, p_{ij} in the frequency of j th allele for the i th marker, and summed over on alleles PIC value exceeding 0.5 indicated presence of polymorphism for the alleles.

$$PIC = 1 - \sum_{j=1}^n (p_{ij})^2$$

Where, p_{ij} in the frequency of j th allele for the i th marker, and summed over on alleles PIC value exceeding 0.5 indicated pre

Chapter - 4

RESULTS AND DISCUSSIONS

This chapter presents the findings of the current study on titled “**Population Dynamics and Stand Structure of *Pinus gerardiana* Wall. in the Dry Temperate Forests of Himachal Pradesh**” The investigation was conducted across four sites in Kinnaur District and one in Chamba District, Himachal Pradesh, India. The key results obtained during the study are systematically presented under the following main headings:

4.1 Morphological traits and stand structure

4.1.1 Growth traits

4.1.2 Needle, cone and seed characteristics

4.1.3 Stand structure

4.2 Phytosociological insights

4.3 Natural regeneration and soil nutrient interactions

4.4 Socioeconomic relevance

4.5 Advances in molecular research

4.1 MORPHOLOGICAL TRAITS AND STAND STRUCTURE

4.1.1 Growth traits

4.1.1.1 Variability estimates among genotypes

All *Pinus gerardiana* (chilgoza pine) genotypes were evaluated for various growth traits, including height, diameter at breast height, crown width, crown projection ratio, and solar influx during the summers month (March to June) of 2023-2024. The differences in growth characteristics among the genotypes were analysed (Table 4) and found to be significant.

The tallest genotype was observed in Kilba (T9, 27.00 m), while the shortest was in Pooh (T16, 12.50 m). The largest DBH was recorded in Moorang (T11, 75.00 cm), while the smallest was in Pooh (T16, 38.50 cm). The crown width ranges from 7.50 m (T23, Pangi) to 12.00 m (T3, Kalpa and T24, Pangi). The highest value (16.75, T3, Kalpa) indicates greater crown spread relative to height, while the lowest (12.15, T18, Pooh) suggests a more compact crown structure. The highest solar influx (24.55 $\mu\text{mol m}^{-2} \text{s}^{-1}$, T7, Kilba) suggests greater light interception, while the lowest (20.55 $\mu\text{mol m}^{-2} \text{s}^{-1}$, T19, Pooh) may indicate more shaded conditions or differences in canopy density.

Tree growth parameters such as height, diameter at breast height (DBH), and crown width provide critical insights into species adaptation, site suitability, and resource acquisition strategies (Boratynska *et al.* (2014). The present study revealed significant variations in these parameters across

different genotypes and locations, reflecting the influence of environmental conditions, genetic potential, and site-specific growth factors. The tallest genotype (T9, 27.00 m) observed in Kilba suggests favorable growth conditions such as optimal soil fertility, moisture availability, and lower climatic stress, which have been associated with enhanced height growth in trees (Alia *et al.* 2001; Kumar *et al.* 2016). In contrast, the shortest genotype (T16, 12.50 m) in Pooh may indicate limitations in resource availability or climatic constraints such as lower precipitation or temperature extremes, which can restrict vertical growth (Kumar *et al.* 2013). Similarly, DBH variations reflect differences in biomass accumulation and growth strategies. The largest DBH (T11, 75.00 cm) recorded in Moorang suggests favorable growing conditions that support greater radial growth, possibly due to higher nutrient availability or reduced competition (Kumar *et al.* 2015).

Table 4: Variation in the mean performance of growth traits among *Pinus gerardiana* genotypes in Himachal Pradesh

Population	Genotypes	Height (m)	Diameter (cm)	Crown width (m)	Crown projection ratio	Solar influx ($\mu \text{ mol}^{-1} \text{ m}^2 \text{ s}^{-1}$)
Kalpa	T1	22.00	51.80	10.00	16.26	24.22
	T2	24.00	55.40	8.00	16.22	24.08
	T3	21.00	48.30	12.00	16.75	24.11
	T4	18.00	35.60	11.00	16.46	24.09
	T5	17.00	42.50	9.80	16.35	23.98
Kilba	T6	18.00	58.50	9.80	16.02	23.88
	T7	20.50	62.60	10.50	16.11	24.55
	T8	24.50	45.80	11.50	15.44	22.87
	T9	27.00	65.80	12.00	15.33	23.87
	T10	17.00	51.50	8.80	15.23	23.44
Moorang	T11	18.00	75.00	9.50	15.88	21.88
	T12	17.00	60.00	7.80	16.02	21.76
	T13	15.00	72.00	8.50	16.34	20.88
	T14	20.00	65.00	10.00	15.66	21.94
	T15	24.00	68.00	8.50	15.45	22.76
Pooh	T16	12.50	38.50	11.50	14.55	20.64
	T17	16.00	64.00	9.50	14.08	21.66
	T18	18.00	68.00	8.00	12.15	20.88
	T19	17.00	58.80	11.50	15.09	20.55
	T20	20.00	72.00	10.50	14.88	21.66
Pangi	T21	15.50	41.00	8.80	15.77	22.45
	T22	12.50	34.60	11.50	16.08	23.77
	T23	15.00	70.00	7.50	16.22	21.88
	T24	16.00	64.90	12.00	13.88	23.22
	T25	14.00	46.80	9.50	15.66	21.66
	Mean	18.40	56.70	9.90	15.50	22.70
	SE	0.70	2.40	0.30	0.20	0.20
	CV	19.80	20.80	13.90	6.30	5.40

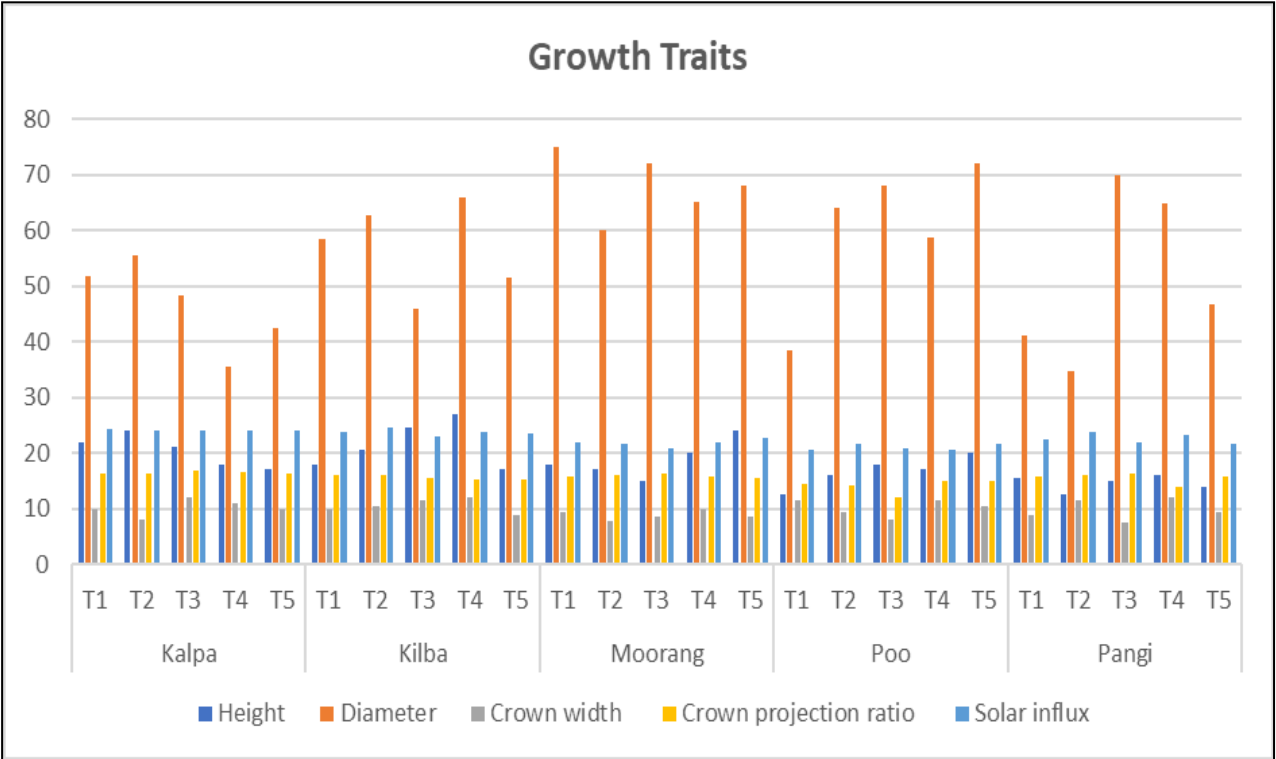


Fig. 2. Graphical depiction of variation in growth traits of *Pinus gerardiana* in different study sites

Crown width is a crucial parameter influencing light interception, photosynthesis, and overall growth potential. The range observed (7.50 m in T23, Pangi, to 12.00 m in T3, Kalpa and T24, Pangi) aligns with findings that canopy architecture varies with genetic and environmental interactions (Sharma *et al.* 2017). A higher crown spread-to-height ratio (16.75, T3, Kalpa) indicates a broader canopy, which may enhance light capture and biomass production (Zou *et al.* 2015). Solar influx is directly related to light interception and photosynthetic efficiency. The highest value ($24.55 \mu\text{mol m}^{-2} \text{s}^{-1}$, T7, Kilba) suggests greater light availability, which can enhance photosynthetic rates and growth (Kumar *et al.* 2015). Overall, these findings highlight the intricate relationships between tree morphology, environmental conditions, and genetic factors. Future studies should incorporate long-term monitoring and physiological assessments to further understand the adaptability and productivity of these genotypes across varying ecological conditions.

4.1.1.2 Variability estimates among population

The highest mean height (21.40 m) was observed in Kilba, followed closely by Kalpa (20.40 m). The lowest height (14.60 m) was recorded in Pangi, indicating possible growth limitations in this region. Moorang (61.99 cm) and Pooh (60.46 cm) had the largest DBH, while Kalpa (48.76 cm) had the smallest. The widest crowns were found in Kilba (10.52 m) and Kalpa (10.16 m), whereas Moorang (9.26 m) had the lowest (Table 5). The highest crown projection ratio was observed in Kalpa (16.41), while the lowest was in Pooh (14.15). The highest solar influx was recorded in Kalpa ($24.09 \mu\text{mol m}^{-2} \text{s}^{-1}$), while the lowest was in Pooh ($21.08 \mu\text{mol m}^{-2} \text{s}^{-1}$). The results revealed significant variations in these parameters across different genotypes and populations, reflecting the influence of environmental conditions, genetic potential, and site-specific growth factors (Pretzsch and Schutze, 2005; Kumar *et al.* 2013)

Table 5: Pattern of variation of growth traits among different populations of *Pinus gerardiana* in Himachal Pradesh

S. No.	Height (m)	Diameter (cm)	Crown width (m)	Crown projection ratio	Solar influx ($\mu\text{mol}^{-1} \text{m}^2 \text{s}^{-1}$)
Kalpa	20.40 ^{ab}	48.76 ^b	10.16 ^a	16.41 ^a	24.09 ^a
Kilba	21.40 ^a	49.94 ^b	10.52 ^a	15.63 ^a	23.72 ^a
Moorang	18.80 ^{ab}	61.99 ^a	9.26 ^b	15.87 ^a	21.84 ^b
Pooh	16.70 ^b	60.46 ^a	9.80 ^{ab}	14.15 ^b	21.08 ^c
Pangi	14.60 ^b	58.84 ^{ab}	10.06 ^{ab}	15.52 ^a	22.59 ^b
CD	4.48	9.10	0.80	1.06	0.75
CV	18.02	13.10	6.42	5.04	2.46

4.1.1.3 Genetic analysis

The genetic parameters for these growth traits were evaluated, and the results are summarized in Table 6. Diameter at Breast Height (DBH) exhibited the highest phenotypic (33.11%) and genotypic (21.69%) coefficients of variation, indicating substantial variability. DBH also demonstrated the highest genetic gain (29.27%) and genetic advance (16.58), making it a key trait for selection. In contrast, Solar Influx had the highest heritability (89.51%), suggesting strong genetic control and minimal environmental influence.

The evaluation of genetic parameters for growth traits provides valuable insights into the potential for genetic improvement in tree breeding programs. In this study, Diameter at Breast Height (DBH) exhibited the highest phenotypic (33.11%) and genotypic (21.69%) coefficients of variation (PCV and GCV, respectively), suggesting substantial genetic and environmental variability. High PCV and GCV values indicate that selection for DBH can be effective, as a significant portion of the observed variation is due to genetic differences (Falconer and Mackay, 1996). Moreover, DBH demonstrated the highest genetic gain (29.27%) and genetic advance (16.58), reinforcing its suitability as a selection criterion in breeding programs. Genetic gain represents the expected improvement per selection cycle, and a high genetic advance suggests that directional selection for DBH will result in notable progress in future generations (Burton and De Vane, 1953). The strong genetic contribution to DBH variation makes it a prime candidate for genetic improvement strategies, particularly in commercial forestry applications where growth rate and biomass accumulation are key economic traits (Thakur *et al.* 2014). The combination of high heritability and substantial genetic advance for DBH suggests that this trait responds well to selection and can be effectively improved in breeding programs (Matziris, 2000). The high heritability of Solar Influx further implies that environmental factors have a limited role in shaping this trait, making it a stable selection criterion (Zobel and Talbert, 1984).

Table 6: Estimates of variability and genetic parameters for growth traits among *Pinus gerardiana* genotypes in Himachal Pradesh

Trait	Mean	Variance			Coefficient of variation		Heritability (h ² %)	Genetic advance	Genetic gain (%)
		Environ-mental	Geno-typic	Pheno-typic	Geno-typic	Pheno-typic			
DBH (cm)	56.70	200.90	151.0	351.90	21.69	33.11	42.91	16.58	29.27
Height (m)	18.40	10.97	5.43	16.40	12.67	22.03	33.09	2.76	15.02
Crown width (cm)	9.90	2.57	0.29	2.86	5.47	17.04	10.30	0.36	3.61
Crown projection ratio	15.50	0.61	0.96	1.57	6.32	8.09	61.73	1.58	10.18
Solar influx ($\mu \text{ mol}^{-1} \text{ m}^2 \text{ s}^{-1}$)	22.70	0.31	2.55	2.86	7.04	7.46	89.51	3.10	13.69

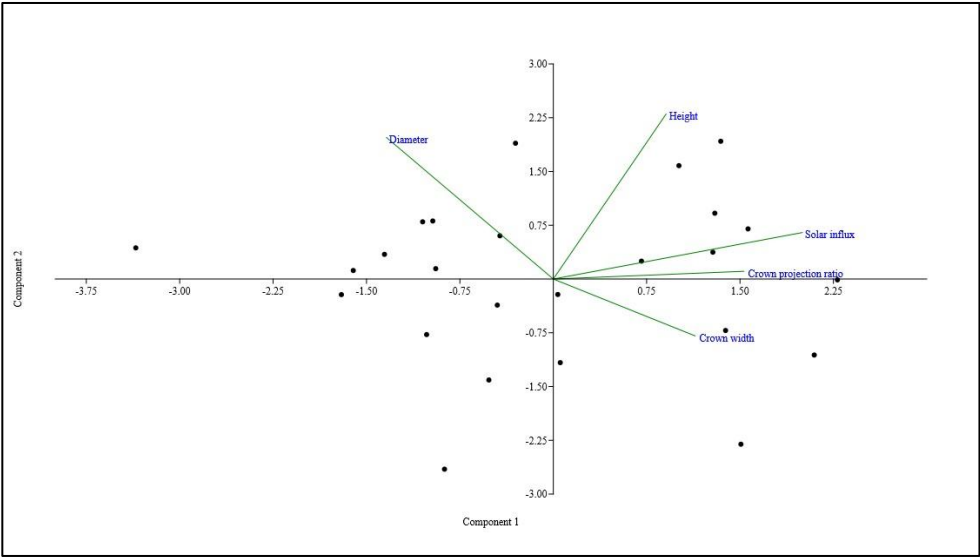


Fig. 3. (a)Biplot representation of different growth traits of *Pinus gerardiana*

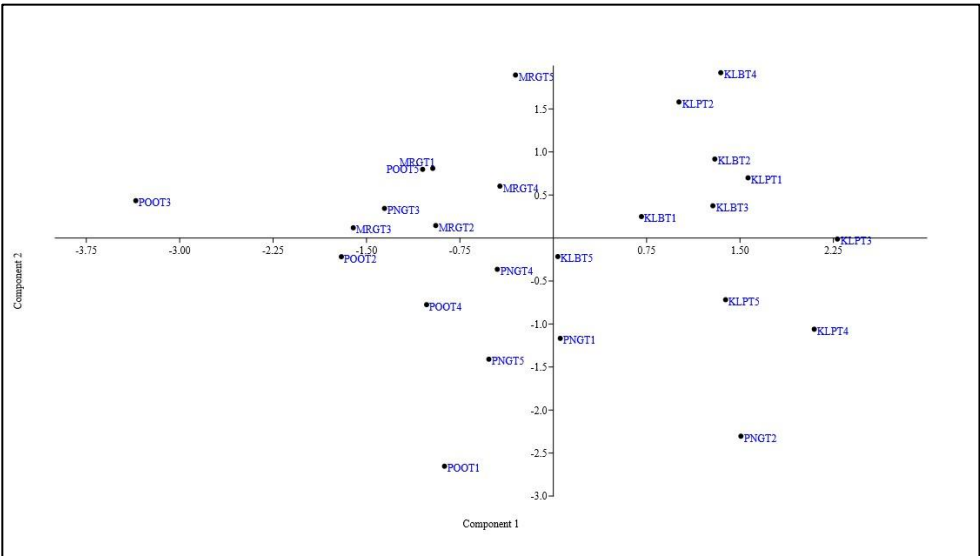


Fig. 3. (b)Biplot representation of genotypes of *Pinus gerardiana* on the basis of growth traits

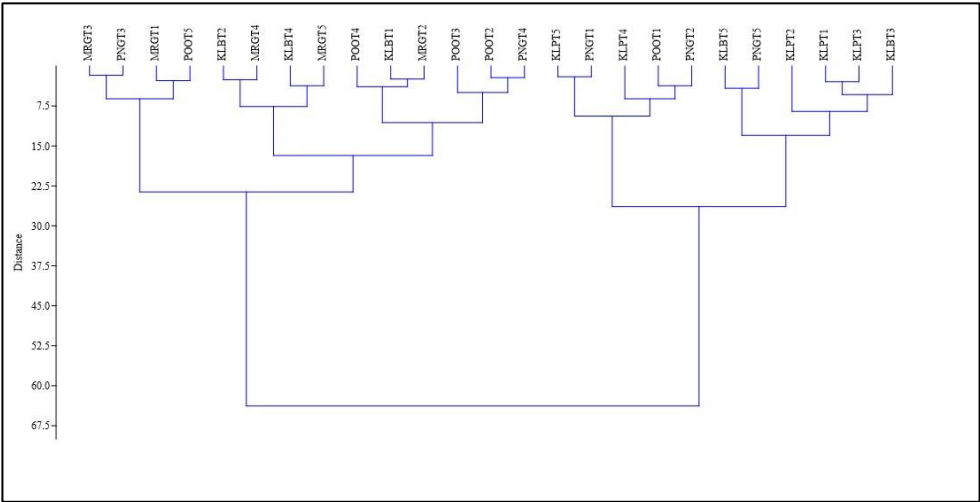


Fig. 4. Dendrogram based on cluster analysis of *Pinus gerardiana* genotypes based on growth traits

4.1.1.4 Correlation studies

Correlation study was performed on growth parameters such as height, DBH, crown width, crown projection ratio and solar influx with each other (Table 7). DBH was significant with height (0.56) at 5 per cent level of significance, crown projection ratio was significant with crown width (0.59) at 1 per cent level of significance. These correlations highlight the potential for indirect selection, where improving one trait could positively impact another. Future studies incorporating genetic correlation and path analysis could provide deeper insights into causal relationships among these growth parameters (Grattapaglia and Resende, 2011; Bhat *et al.* 2016).

Table 7: Correlation for the growth traits among *Pinus gerardiana* genotypes in Himachal Pradesh

Traits	Height (m)	Diameter (cm)	Crown Width (m)	Crown Projection Ratio	Solar Influx ($\mu \text{ mol}^{-1} \text{ m}^2 \text{ s}^{-1}$)
Height (m)	1				
Diameter (cm)	0.56*	1			
Crown width (m)	0.12	-0.35	1		
Crown projection ratio	0.12	-0.28	0.59**	1	
Solar influx ($\mu \text{ mol}^{-1} \text{ m}^2 \text{ s}^{-1}$)	0.45	-0.34	0.26	0.002	1

*Significant at 5 per cent level of significance

**Significant at 1 per cent level of significance

4.1.1.5 Principal component analysis

Principal Component Analysis (PCA) is a dimensionality-reduction technique that simplifies large datasets by transforming a high number of variables into a smaller set while retaining most of the original information. In the growth data, Table 8 shows the factor pattern and a summary of PCA. Only three components were found to have eigen values greater than one and these components were kept for additional genetic study. Eigen values less than one are not taken into account any further. These variables accounted for 85.5 per cent of the variation.

For component I ($\lambda_1=1.96$) explaining 39.10 per cent variation, Height was attached with maximum loading value (0.91), followed by DBH (0.80); while as crown width had lowest value (0.65). Component II ($\lambda_2=1.31$) explained 26.2 per cent of variation with maximum loading value attached to solar influx (0.68); followed by DBH (0.57). Component III ($\lambda_3=1.01$) explained 20.2 per cent of variation with maximum loading value attached to crown projection ratio (0.43). This aligns with earlier studies where height and DBH were key selection criteria in tree improvement (Zobel and Talbert, 1984; Banderas *et al.* 2009). These findings suggest that Height, DBH, and Solar Influx are key selection traits, while Crown Projection Ratio also plays a role in structural development. Future selection strategies should focus on these principal components to optimize tree growth and productivity (Grattapaglia and Resende, 2011; Huang *et al.* 2015).

Table 8: Principal component analysis for growth traits among *Pinus gerardiana* genotypes in Himachal Pradesh

Trait	Principal Components					Communalities
	I	II	III	IV	V	
Height (m)	0.91	-0.24	0.03	-0.4	0.02	0.91
Diameter (cm)	0.80	0.57	0.03	0.04	-0.2	0.84
Crown width (m)	0.65	-0.6	-0.44	0.12	-0.1	0.88
Crown projection ratio	0.78	-0.42	0.43	0.18	0.04	0.83
Solar influx ($\mu \text{ mol}^{-1} \text{ m}^2 \text{ s}^{-1}$)	0.69	0.68	-0.14	0.07	0.17	0.82
Eigenvalues (λ)	1.96	1.31	1.01	0.45	0.27	
Percentage of variance	39.10	26.20	20.20	9.00	5.50	
Cumulative percentage of variance	39.10	65.30	85.50	9.45	100	

4.1.1.6 Genetic divergence studies

The 25 genotypes were divided into three clusters based on their growth features (Table 9). Cluster II had the most genotypes (11), with genotypes numbered 7, 9, 11, 13, 14, 15, 17, 18, 20, 23 and 24, whereas cluster III had the fewest (6), with genotypes numbered 24, 5, 16, 21, 22 and 25. Cluster I had 8 genotypes (1, 2, 3, 6, 8, 10, 12 and 19). The clustering pattern highlights genetic variability, which is crucial for selection and hybridization strategies. Future studies integrating molecular markers can further refine these groupings for targeted breeding (Aslam *et al.* 2011; Huang *et al.* 2015).

Table 9: Cluster for genetic divergence in growth traits among *Pinus gerardiana* genotypes in Himachal Pradesh

Cluster	Number of Genotypes	Genotypes
1	8	1, 2, 3, 6, 8, 10, 12, 19,
2	11	7, 9, 11, 13, 14, 15, 17, 18, 20, 23, 24,
3	6	4, 5, 16, 21, 22, 25,

4.1.2 Needle, cone and seed characteristics

4.2.2.1 Variability estimates among genotype

As presented in the Table 10, significant variation was observed in needle length. The shortest needle length was recorded in T24 (7 cm), while the longest was observed in T17 (9.2 cm). For cone length, the maximum was found in T6 (16.6 cm), whereas the minimum was recorded in T18 (10.2 cm). Similarly, cone width varied from a maximum of 10.7 cm in T11 to a minimum of 8.2 cm in T7.

Regarding seed traits, the longest seed was observed in T12 (23.4 mm), while the shortest was in T21 (17 mm). The widest seed was found in T20 (7.3 mm), whereas the narrowest was in T1 (5.2 mm). For 100-seed weight, the highest value was recorded in T20 and T7 (59 g), while the lowest was in T25 (40 g).

The observed variation in needle length, cone dimensions, and seed traits suggests significant genetic and environmental influences on these characteristics. Needle length variability (7–9.2 cm) may be linked to site-specific adaptations, as reported in conifer studies (Song *et al.* 2012). Cone size differences, with lengths ranging from 10.2 cm to 16.6 cm and widths from 8.2 cm to 10.7 cm, align with findings that local environmental factors influence reproductive structures (Nikolic *et al.* 2015). Seed traits, including length (17–23.4 mm) and width (5.2–7.3 mm), indicate genetic diversity crucial for selection programs (Sharma *et al.* 2019). The 100-seed weight variation (40–59 g) highlights differences in resource allocation, supporting previous research on seed mass and viability relationships (Kumar *et al.* 2016). These findings provide a basis for selecting superior genotypes for breeding and conservation.

Table 10: Variation in the mean performance for needle, cone and seed characteristics of *Pinus gerardiana* genotypes in Himachal Pradesh

Population	Genotypes	Needle Length (cm)	Cone length (cm)	Cone width (cm)	Seed length (mm)	Seed width (mm)	100 seed weight (g)
Kalpa	T1	7.6	11.3	8.9	18.3	5.2	48.3
	T2	7.8	15.3	8.5	19.3	5.4	58.3
	T3	7.5	14.5	9.2	20.4	6.0	51.0
	T4	8.3	13.7	8.9	20.7	5.9	56.0
	T5	7.6	14.6	9.1	20.8	5.9	54.0
Kilba	T6	7.0	16.6	9.2	20.6	6.4	52.3
	T7	7.5	15.3	8.2	20.8	6.0	59.0
	T8	7.0	12.6	9.0	19.8	6.0	58.0
	T9	6.8	11.7	9.2	20.7	6.1	50.0
	T10	7.8	14.1	10.0	21.9	6.3	52.7
Moorang	T11	8.0	11.6	10.7	22.1	6.1	56.0
	T12	8.0	12.7	9.0	23.4	6.1	53.7
	T13	7.7	14.6	9.3	21.9	6.8	54.7
	T14	8.2	12.5	9.1	21.8	6.6	52.7
	T15	8.5	16.0	9.5	21.9	6.6	52.7
Pooh	T16	8.6	13.5	9.2	21.7	6.3	47.7
	T17	9.2	11.7	9.2	21.9	6.6	52.7
	T18	8.1	10.2	9.6	22.1	6.9	51.7
	T19	8.9	15.1	9.4	22.2	6.9	54.0
	T20	8.1	13.4	9.1	22.8	7.3	59.0
Pangi	T21	7.6	11.8	9.5	17.0	5.9	41.0
	T22	7.6	14.8	9.2	17.2	5.8	42.3
	T23	7.4	12.2	8.8	17.5	5.8	45.0
	T24	7.1	15.7	9.1	17.2	6.0	44.3
	T25	7.3	13.7	9.6	17.5	6.1	40.0
	Mean	7.8	13.6	9.2	20.5	6.2	51.5
	SE	0.1	0.3	0.1	0.4	0.1	1.1
	CV	7.2	11.9	4.9	9.2	7.3	10.2

4.2.2.2 Variability estimates among population

The highest needle length (8.56 cm) was observed in Pooh, followed closely by Moorang (8.07 cm). The maximum cone length (14.06 cm) was found in Kilba and minimum cone length was in Pooh (12.78 cm). The maximum cone width was recorded in Moorang 9.51 cm, and minimum cone width was in Kalpa 8.91 cm. indicating possible growth limitations in this region. Moorang (61.99 cm) and Pooh (60.46 cm) had the largest DBH, while Kalpa (48.76 cm) had the smallest. The widest crowns were found in Kilba (10.52 m) and Kalpa (10.16 m), whereas Moorang (9.26 m) had the narrowest (Table 11). The highest crown projection ratio was observed in Kalpa (16.41), while the lowest was in Pooh (14.15). The highest solar influx was recorded in Kalpa ($24.09 \mu\text{mol m}^{-2} \text{s}^{-1}$), while the lowest was in Pooh ($21.08 \mu\text{mol m}^{-2} \text{s}^{-1}$). Significant variation in needle length, cone traits, DBH, crown structure, and solar influx across regions suggests both genetic and environmental influences on growth (Kumar *et al.* 2015; Pretzsch, 2014). These differences highlight growth potential and selection criteria for tree improvement programs.

Table 11: Pattern of variation of needle, cone and seed characteristics among different population of *Pinus gerardiana* in Himachal Pradesh

S. No.	Needle Length (cm)	Cone length (cm)	Cone width (cm)	Seed length (mm)	Seed width (mm)	100 seed weight (g)
Kalpa	7.77 ^{bc}	13.88 ^a	8.91 ^a	19.91 ^b	5.69 ^d	53.53 ^a
Kilba	7.23 ^c	14.06 ^a	9.13 ^a	20.76 ^b	6.15 ^c	54.4 ^a
Moorang	8.07 ^b	13.48 ^a	9.51 ^a	22.21 ^a	6.44 ^b	53.94 ^a
Pooh	8.56 ^a	12.78 ^a	9.3 ^a	22.14 ^a	6.8 ^a	53.00 ^a
Pangi	7.41 ^c	13.64 ^a	9.25 ^a	17.26 ^c	5.92 ^c	42.53 ^b
CD	0.47	N/A	N/A	0.89	0.29	4.42
CV	4.48	13.59	4.55	3.21	3.49	6.35

4.2.2.3 Genetic analysis

The genetic parameters for needle, cone, and seed characteristics were evaluated, and the results are summarized in Table 12. Needle length exhibited the highest phenotypic (15.70%) and genotypic (15.04%) coefficients of variation, indicating substantial variability. It also demonstrated the highest genetic gain (29.69%) and heritability (92.23%), making it a key trait for selection. In contrast, 100-seed weight had the highest genetic advance (8.19%), suggesting strong genetic control with minimal environmental influence. The high heritability (92.23%) and genetic gain (29.69%) suggest that this trait is largely controlled by genetic factors with minimal environmental influence, making it a reliable trait for selection (Sehgal *et al.* 1995; Guller *et al.* 2012). These findings suggest that needle length and 100-seed weight are key traits for selection, and their high genetic control makes them ideal targets for future breeding programs aimed at improving tree growth and

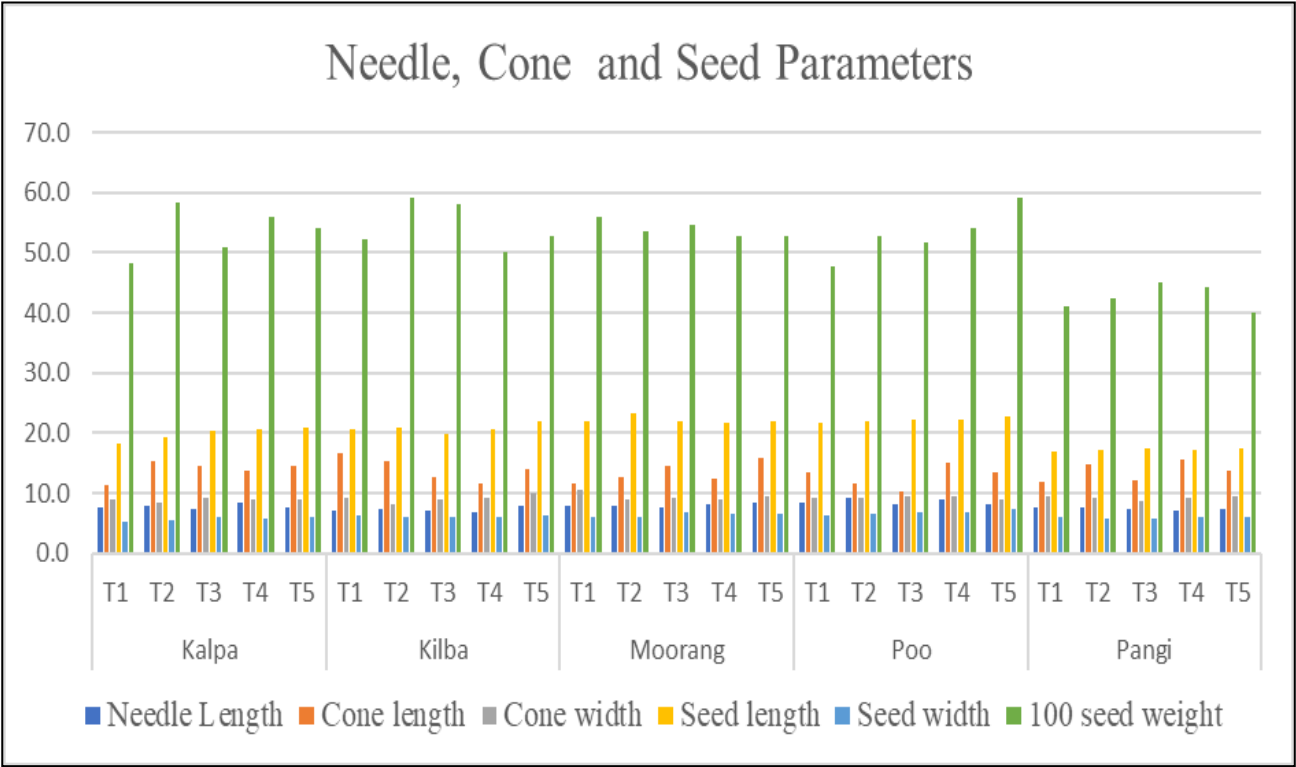


Fig. 5 Graphical depiction of variation in needle, cone and seed parameters of *Pinus gerardiana* in different study sites



Plate 2. Needle and cone of *Pinus gerardiana* in its natural habitat

adaptability (Zobel and Talbert, 1984). Further quantitative genetic studies and marker-assisted selection could enhance genetic gains in these traits.

Table 12: Estimates of variability and genetic parameters for needle, cone and seed characteristics among *Pinus gerardiana* genotypes in Himachal Pradesh

Trait	Mean	Variance			Coefficient of variation		Heritability (h ² %)	Genetic advance	Genetic gain (%)
		Environ-mental	Geno-typic	Pheno-typic	Geno-typic	Pheno-typic			
Needle Length (cm)	7.80	0.12	1.38	1.50	15.04	15.70	92.23	2.32	29.69
Cone length (cm)	13.60	3.40	0.44	3.84	4.87	14.44	11.67	0.46	3.39
Cone width (cm)	9.20	0.35	0.02	0.38	1.57	6.57	5.54	0.07	0.77
Seed length (mm)	20.5	0.43	4.04	4.48	9.82	10.34	90.23	3.94	19.24
Seed width (mm)	6.20	0.05	0.18	0.23	6.86	7.70	79.55	0.78	12.59
100 seed weight (g)	51.5	10.69	23.15	33.85	9.35	11.30	68.46	8.19	15.92

4.2.2.4 Correlation analysis

Correlation study was performed on needle, cone, and seed characteristics with each other (Table 13). Cone width was significant with needle length (0.46) at 5 per cent level of significance, seed length was significant with needle length (0.55) at 5 per cent level of significance and seed width was significant with needle length (0.46) at 5 per cent level of significance and with seed length (0.66) at 1 per cent level of significance. 100 seed weight with seed length (0.72) at 1 per cent level of significance. These correlations highlight that needle length, seed dimensions, and seed weight are interrelated traits, which can be used for indirect selection in breeding programs. Selecting for longer needles may simultaneously improve seed traits, leading to enhanced reproductive success and seedling establishment (Sharma *et al.* 2013).

Table 13: Correlation for needle, cone and seed characteristics among *Pinus gerardiana* genotypes in Himachal Pradesh

Traits	Needle Length (cm)	Cone length (cm)	Cone width (cm)	Seed length (mm)	Seed width (mm)	100 seed weight (g)
Needle Length (cm)	1					
Cone length (cm)	-0.10	1				
Cone width (cm)	0.46*	-0.24	1			
Seed length (mm)	0.55*	-0.05	0.20	1		
Seed width (mm)	0.46*	0.02	0.29	0.66**	1	
100 seed weight (g)	0.25	0.13	-0.19	0.72**	0.28	1

*Correlation is significant at the 0.05 level.

** Correlation is significant at the 0.01 level.

4.2.2.5 Principal component analysis

Principal Component Analysis (PCA) is a dimensionality-reduction technique that simplifies large datasets by transforming a high number of variables into a smaller set while retaining most of the original information. In the growth data, Table 14 shows the factor pattern and a summary of PCA. Only two components were found to have eigen values greater than one and these components were kept for additional genetic study. Eigen values less than one are not taken into account any further. These variables accounted for 45.50 per cent of the variation. For component I ($\lambda_1=2.73$) explaining 45.50 per cent variation, needle length was attached with maximum loading value (0.988), followed by 100 seed weight (0.84). For component II ($\lambda_2=1.29$) explaining 21.60 per cent variation, 100 seed weight was attached with maximum loading value (0.48), followed by needle length (0.44). Component I (explaining 45.50% variation) was strongly influenced by needle length (loading = 0.988) and 100-seed weight (0.84), indicating that these traits play a dominant role in growth differentiation and selection (Banderas *et al.* 2009). Component II (explaining 21.60% variation) also emphasized 100-seed weight (0.48) and needle length (0.44), reinforcing their genetic importance across different PCs (Singh, 2006). These findings suggest that needle length and seed weight are crucial selection traits for breeding programs, as they contribute significantly to overall genetic variation. Future genetic studies integrating molecular markers may further validate these results for enhanced selection strategies (Grattapaglia and Resende, 2011; Huang *et al.* 2015; Bhat, 2015).

Table 14: Principal component analysis for needle, cone and seed characteristics among *Pinus gerardiana* genotypes in Himachal Pradesh

Trait	Principal Components						Communalities
	I	II	III	IV	V	VI	
Needle Length (cm)	0.86	0.44	-0.19	0.13	-0.04	0.12	0.97
Cone length (cm)	0.52	-0.72	-0.16	0.132	-0.42	-0.01	0.82
Cone width (cm)	0.63	0.09	0.51	-0.57	-0.12	-0.03	0.67
Seed length (mm)	0.58	-0.44	-0.52	-0.28	0.35	-0.02	0.79
Seed width (mm)	0.53	-0.40	0.61	0.35	0.27	0.01	0.82
100 seed weight (g)	0.84	0.481	-0.12	0.193	-0.03	-0.12	0.95
Eigenvalues (λ)	2.73	1.29	0.97	0.58	0.39	0.03	
Percentage of variance	45.50	21.60	16.20	9.70	6.60	0.50	
Cumulative percentage of variance	45.50	67.10	83.30	9.30	99.50	100	

4.2.2.6 Genetic divergence studies

The 25 genotypes were divided into three clusters based on their growth features (Table 15). Cluster III had the most genotypes (14), with genotypes numbered 71, 3, 5, 6, 9, 10, 12, 13, 15).

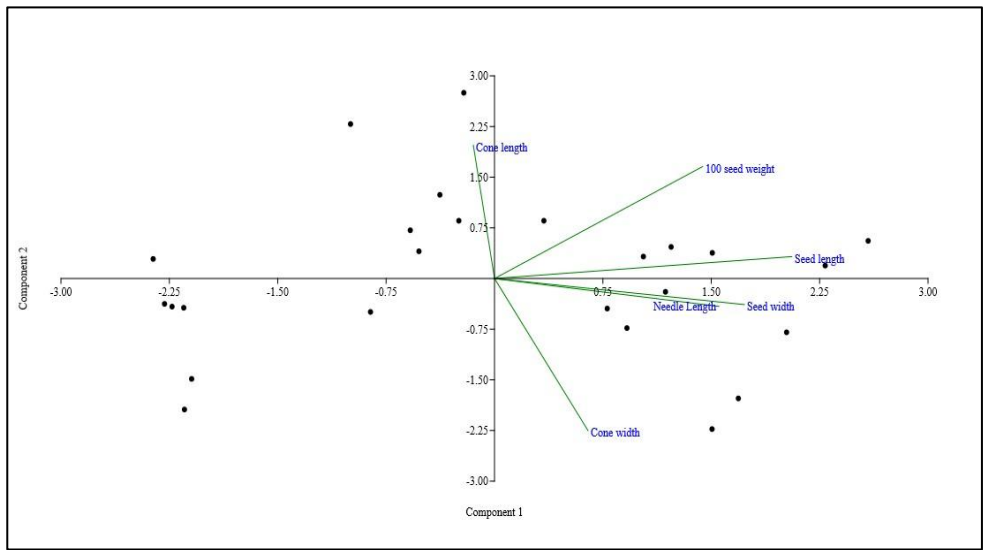


Fig. 6 (a) Biplot representation of different needle, cone and seed parameters of *Pinus gerardiana*

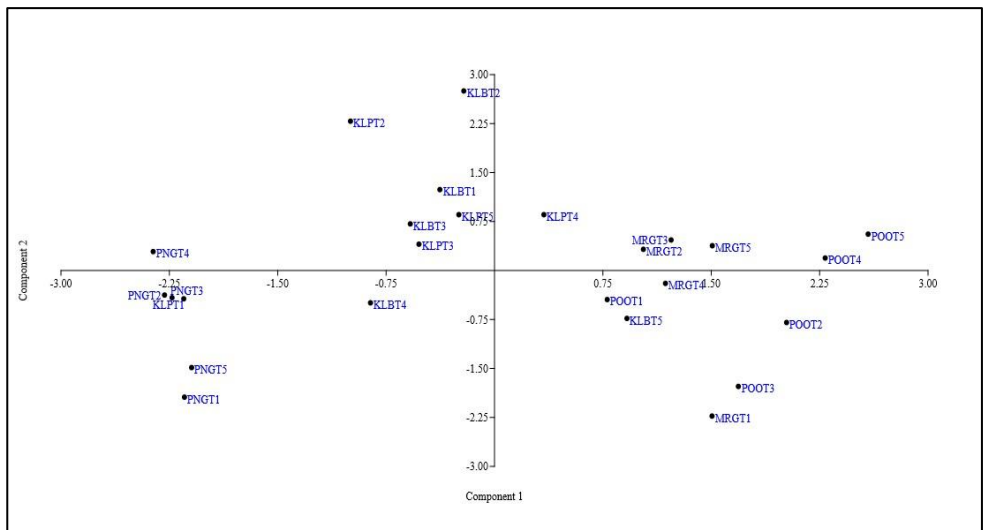


Fig. 6 (b) Biplot representation of genotypes of *Pinus gerardiana* on the basis of needle, cone and seed parameters

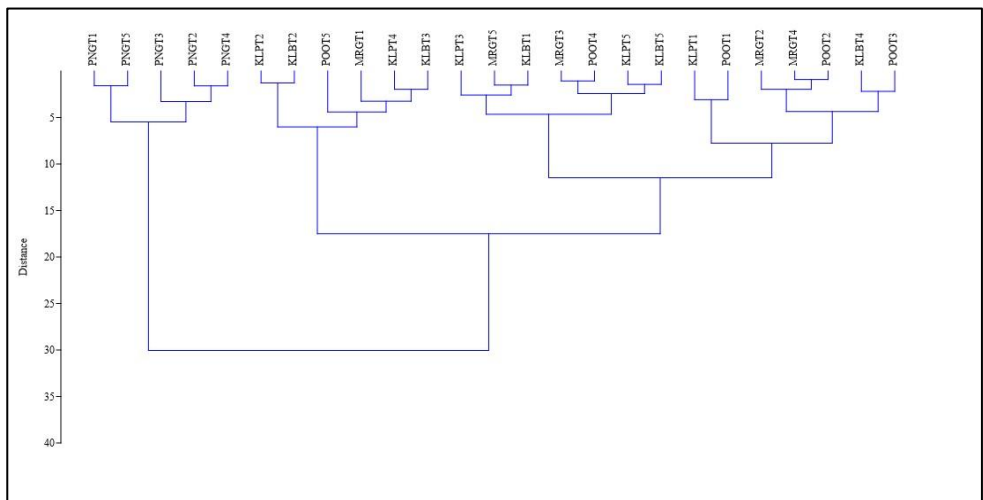


Fig. 7 Dendrogram based on cluster analysis of *Pinus gerardiana* genotypes based on needle, cone and seed parameters

14, 15, 16, 17, 18 and 19, whereas cluster I had the fewest (5), with genotypes numbered 21, 22, 23, 24 and 25. Cluster II had 6 genotypes (2, 4, 7, 8, 11 and 20). These findings emphasize the importance of genetic diversity in breeding programs, allowing for the selection of high-performing genotypes for specific environmental conditions (Aslam *et al.* 2011; Bhat *et al.* 2015).

Table 15: Cluster for genetic divergence in needle, cone and seed characteristics among *Pinus gerardiana* genotypes in Himachal Pradesh

Cluster	Number of Genotypes	Genotypes
1	5	21, 22, 23, 24, 25,
2	6	2, 4, 7, 8, 11, 20,
3	14	1, 3, 5, 6, 9, 10, 12, 13, 14, 15, 16, 17, 18, 19,

4.1.3 Stand Characteristics

Kilba had the highest total tree percentage (64.33%), indicating a dominant presence of trees across various diameter classes. This suggests either a favourable growing environment or successful regeneration. Pangi followed with 42.50 per cent, showing a well-distributed population, particularly in mid-to-large diameter classes. Moorang (35.37%) maintained a balanced distribution across all size classes, reflecting a mix of young and mature trees. Pooh (30.86%) had significant representation in the mid-range diameter classes (30–50 cm), indicating ongoing regeneration but fewer older trees. Kalpa had the lowest total tree percentage (30.24%), suggesting either slower growth or a decline in population density. Kilba showed a strong peak in the 30–50 cm range, indicating a large number of young to mid-sized trees. Moorang had a relatively even distribution, with representation even in the larger diameter classes (80–100 cm). Pangi had a strong presence in the 40–70 cm range, suggesting a mix of mature and regenerating trees. Pooh showed better recruitment in smaller classes (<50 cm) but lower representation in larger classes, pointing to an early-stage forest structure. Kalpa had trees in the mid-size range but lacked larger trees, which may indicate regeneration challenges or recent disturbances. Kilba leads in total tree percentage, followed by Pangi and Moorang. Kalpa and Pooh exhibit lower values, suggesting possible regeneration issues. The distribution across diameter classes indicates varying levels of forest maturity, with some sites showing a more even structure while others are dominated by younger or mid-sized trees. These results align with the findings of Das *et al.* (2021) and Kaushal and Baishya (2021), who also observed the highest density in the middle and lower diameter classes (Table 16).

The variation in total tree percentage and diameter class distribution among locations highlights differences in forest structure, regeneration potential, and environmental adaptability

(Benton and Werner, 1976; Lutz *et al* 2013). Kilba (64.33%) exhibited the highest tree percentage, suggesting a favorable growing environment and strong regeneration, while Kalpa (30.24%) had the lowest, indicating possible growth constraints or disturbances (Kumar *et al.* 2015). The balanced distribution in Moorang (35.37%) and Pangi (42.50%), with trees spanning multiple diameter classes, suggests a stable, regenerating population (Khan *et al.* 1987). Pooh dominance in the 30–50 cm range indicates ongoing recruitment but a lack of older trees, pointing to an early-stage forest structure (Malik *et al.* 2012). The absence of larger trees in Kalpa may indicate regeneration challenges or past disturbances (Dhar and Sundarapandian, 2016). These findings underscore the importance of monitoring tree size distributions for sustainable forest management, with sites like Kilba serving as models for successful regeneration and growth strategies.

Table 16: Stand structure of *Pinus gerardiana* genotypes in Himachal Pradesh

	Diameter Classes (cm)										Total
Sites	<10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	
Kalpa	10	25.00	33.33	43.33	50.00	23.33	16.67	20.00			30.24
Kilba	10.00	25.00	46.67	110.00	106.67	33.33					64.33
Moorang	25.00	20.00	33.33	40.00	46.67	46.67	60.00	36.67	15.00	20.00	35.37
Pooh	13.33	20.00	30.00	50.00	53.33	36.88	33.33	13.33	10.00		30.86
Pangi	20	10.00	33.33	43.33	93.33	46.67	66.67	36.67	10.00		42.50

4.2. Phytosociological insights

4.2.1 Kalpa Forest Range

The data collected in this range revealed the presence of three tree species, nine shrub species, and seventeen herbaceous species. Among the trees, *Pinus gerardiana* was the most dominant (IVI: 212.85), indicating its ecological adaptability and potential economic importance, particularly for nut production (Kumar *et al.* 2015) followed by *Cedrus deodara* (IVI: 45.40) and *Pinus wallichiana* (IVI: 41.75) (Table 17). Among shrubs, *Indigofera cedrorum* had the highest IVI (51.78), possibly due to its adaptive traits such as nitrogen fixation and drought resistance (Kumar *et al.* 2013) indicating its dominance, followed by *Rubus ellipticus* (IVI: 45.11) and *Rosa macrophylla* (IVI: 40.26). The lowest IVI was recorded for *Daphne oleoides* (IVI: 14.07), suggesting its lower abundance, it may be under competitive stress or experiencing regeneration challenges (Prakash *et al.* 2021). In the herbaceous layer, *Artemisia capillaris* exhibited the highest IVI (55.09), making it the most dominant species, likely due to its adaptability to varied soil conditions (Kumar *et al.* 2013), followed by *Anaphalis royleana* (IVI: 29.61) and *Thymus linearis* (IVI: 18.78). The lowest IVI was observed for *Ranunculus hirtellus* (IVI: 8.67), indicating its limited presence in the area.

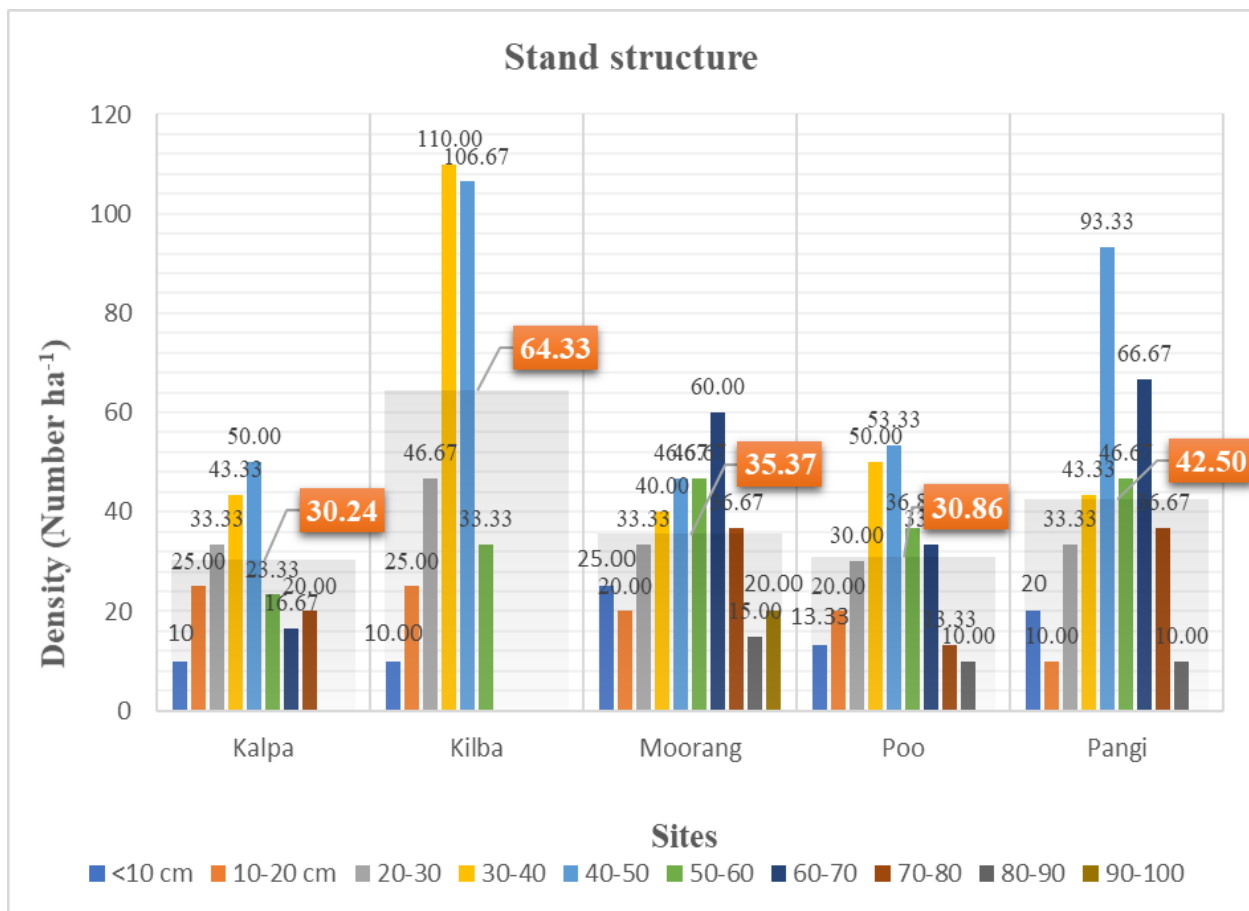


Fig. 8 Stand structure of *Pinus gerardiana* genotypes in Himachal Pradesh

Table 17: Phytosociology of chilgoza pine forests in Kalpa Forest Range of Kinnaur Forest Division, Reckong Peo

Spp.	RD	RF	RBA	IVI
Trees				
<i>Cedrus deodara</i>	5.26	28.57	11.57	45.40
<i>Pinus gerardiana</i>	89.47	42.86	80.52	212.85
<i>Pinus wallichiana</i>	5.26	28.57	7.92	41.75
	100	100	100	300
Shrubs				
<i>Abelia triflora</i>	12.90	12.68	6.65	32.23
<i>Cotoneaster microphyllus</i>	5.81	8.45	14.75	29.01
<i>Daphne oleoides</i>	3.87	5.63	4.57	14.07
<i>Desmodium triflorum</i>	14.19	14.08	6.60	34.88
<i>Indigofera cedrorum</i>	9.03	9.86	32.89	51.78
<i>Lonicera hypoleuca</i>	8.39	9.86	2.73	20.98
<i>Plectranthus rugosus</i>	14.19	12.68	4.80	31.67
<i>Rosa macrophylla</i>	14.19	12.68	13.39	40.26
<i>Rubus ellipticus</i>	17.42	14.08	13.61	45.11
	100	100	100	300
Herbs/grasses				
<i>Adiantum venustum</i>	10.86	9.93	3.92	24.71
<i>Anaphalis royleana</i>	8.57	7.28	13.76	29.61
<i>Artemisia capillaris</i>	10.29	7.95	36.87	55.09
<i>Aster albescens</i>	7.43	6.62	3.41	17.46
<i>Astragalus chlorostachys</i>	4.56	3.31	3.33	10.64
<i>Dianthus angulatus</i>	6.86	7.95	2.94	17.74
<i>Galinsoga ciliata</i>	8.40	7.95	2.78	18.74
<i>Jurinea ceratocarpa</i>	4.60	4.60	2.2	11.45
<i>Polygonatum multiflorum</i>	4.50	4.30	4.50	13.71
<i>Persicaria hydropiper</i>	4.20	3.97	3.29	11.26
<i>Ranunculus hirtellus</i>	3.43	3.31	1.93	8.67
<i>Rosularia rosulata</i>	6.86	7.95	3.02	17.82
<i>Silene songarica</i>	5.71	5.29	2.69	13.71
<i>Thalictrum reniforme</i>	3.43	3.31	2.71	9.45
<i>Thymus linearis</i>	7.43	6.62	4.73	18.78
<i>Verbascum thapsus</i>	4.57	5.29	5.67	15.54
	100	100	100	300

4.2.2 Kilba Forest Range

The data collected in this range revealed the presence of five tree species, eleven shrub species, and fourteen herbaceous species. Among the trees, *Pinus gerardiana* exhibited the highest dominance (IVI: 161.19), highlighting its ecological significance, adaptability, and economic importance, particularly for nut production (Kumar *et al.* 2015). This was followed by *Quercus ilex* (IVI: 54.19) and *Cedrus deodara* (IVI: 34.38). *Olea cuspidata* recorded the lowest IVI (20.83), suggesting its limited distribution, possibly due to habitat specificity or competitive suppression (Kumar *et al.* 2013). Among the shrubs, *Rhus cotinus* had the highest IVI (39.79), indicating its dominance, followed by *Berberis aristata* (IVI: 36.55) and *Rubus ellipticus* (IVI: 34.87). The lowest IVI was observed for *Lonicera hypoleuca* (IVI: 16.78), reflecting its lower presence. In the herbaceous layer, *Artemisia maritima* was the most dominant species (IVI: 57.13), followed by *Potentilla atosanguinea* (IVI: 32.45) and *Thymus linearis* (IVI: 31.06) (Table 18). The lowest IVI was recorded for *Morina longifolia* (IVI: 9.79), indicating its minimal contribution to the vegetation structure. This study underscores the importance of species dominance in ecosystem functioning and highlights key species that contribute to forest stability and biodiversity conservation (Gupta, 1996). Species with lower IVI values may require focused conservation efforts to enhance their population sustainability.

Table 18: Phytosociology of chilgoza pine forests in Kilba Forest Range of Kinnaur Forest Division, Reckong Peo

Spp.	RD	RF	RBA	IVI
Trees				
<i>Cedrus deodara</i>	5.21	21.43	7.74	34.38
<i>Olea cuspidata</i>	4.17	14.29	2.38	20.83
<i>Pinus gerardiana</i>	64.58	21.43	75.18	161.19
<i>Pinus wallichiana</i>	3.13	21.43	4.85	29.41
<i>Quercus ilex</i>	22.92	21.43	9.85	54.19
	100	100	100	300
Shrubs				
<i>Abelia triflora</i>	9.87	8.97	4.25	23.09
<i>Berberis aristata</i>	7.89	7.69	20.96	36.55
<i>Berberis lycium</i>	6.58	6.41	14.46	27.45
<i>Daphne oleoides</i>	11.18	10.26	6.65	28.09
<i>Desmodium triflorum</i>	7.89	8.97	6.95	23.82
<i>Lonicera hypoleuca</i>	6.58	7.69	2.51	16.78
<i>Lonicera quinquelocularis</i>	12.5	8.97	2.99	24.47
<i>Plectranthus rugosus</i>	5.92	10.26	5.91	22.09
<i>Rhus cotinus</i>	8.55	8.97	22.27	39.79

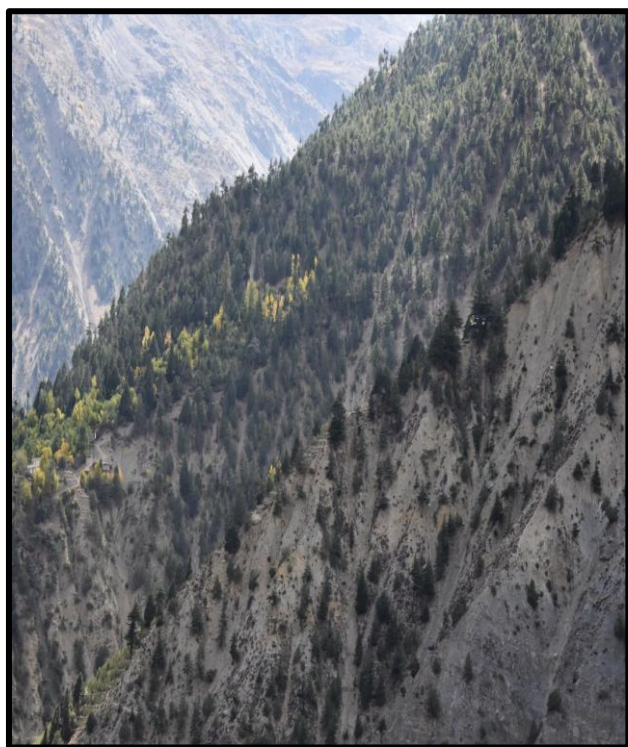
<i>Rosa webbaiana</i>	7.24	8.97	6.77	22.98
<i>Rubus ellipticus</i>	15.79	12.82	6.26	34.87
	100	100	100	300
Herbs/grasses				
<i>Anemone rivularis</i>	9.24	8.78	4.47	22.49
<i>Artemisia maritima</i>	10.33	9.46	37.35	57.13
<i>Cynonchum auriculatum</i>	10.33	10.14	3.16	23.62
<i>Dianthus angulatus</i>	11.41	10.8	3.99	26.21
<i>Erysimum hieraciifolium</i>	5.98	6.76	3.22	15.95
<i>Galium aparine</i>	6.52	7.43	3.39	17.35
<i>Impatiens brachycentra</i>	5.98	6.08	3.66	15.72
<i>Lactuca dissecta</i>	5.43	5.40	1.69	12.53
<i>Morina longifolia</i>	3.80	4.05	1.94	9.79
<i>Potentilla atosanguinea</i>	5.98	5.50	21.06	32.45
<i>Salvia nubicola</i>	4.35	5.40	4.24	13.99
<i>Senecio kashmerianus</i>	4.35	4.05	2.70	11.10
<i>Thymus linearis</i>	11.41	12.16	7.49	31.06
	100	100	100	300

4.2.3 Moorang Forest Range

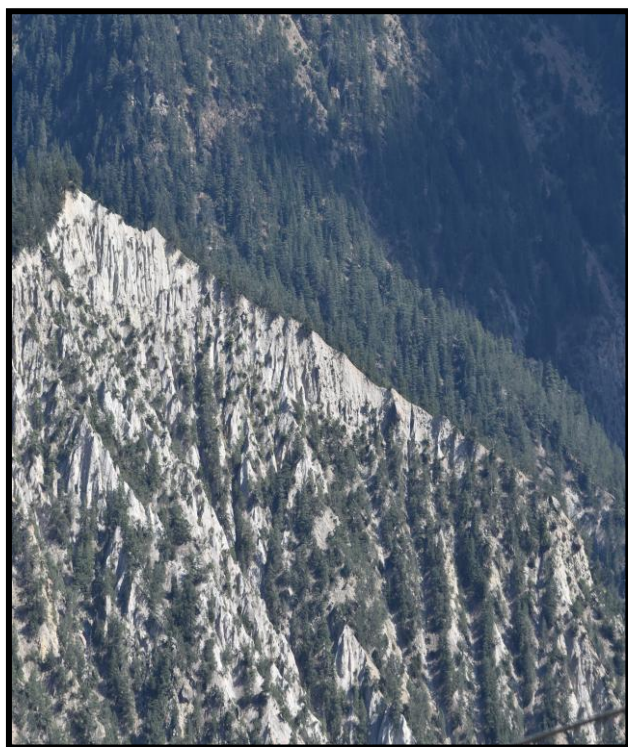
The data collected in this range revealed the presence of four tree species, eight shrub species, and seventeen herbaceous species. Among the trees, *Pinus gerardiana* exhibited the highest dominance (IVI: 177.85), emphasizing its ecological significance. This was followed by *Cedrus deodara* (IVI: 73.16) and *Fraxinus micrantha* (IVI: 37.34). *Pinus wallichiana* had the lowest IVI (11.66), indicating its minimal presence. Among the shrubs, *Rhus cotinus* had the highest IVI (55.28), followed by *Colutea nepalensis* (IVI: 54.75) and *Caragana brevispora* (IVI: 40.76), showing their dominance in the shrub layer (Table 19). The lowest IVI was recorded for *Rosa webbaiana* (IVI: 24.19), suggesting its relatively lower abundance. In the herbaceous layer, *Artemisia capillaris* was the most dominant species (IVI: 49.24), followed by *Artemisia vulgaris* (IVI: 31.36) and *Artemisia scoparia* (IVI: 27.26). The lowest IVI was recorded for *Rumex nepalensis* (IVI: 6.48), indicating its minimal contribution to the vegetation structure, possibly due to site-specific constraints or limited competitive ability (Rawat and Chandra, 2015). This study underscores the importance of species dominance in maintaining ecosystem balance and suggests that species with lower IVI values may require conservation efforts to ensure their long-term sustainability and ecological functions (Singh and Rawat, 2021).

Table 19: Phytosociology of chilgoza pine forests in Moorang Forest Range of Kinnaur Forest Division, Reckong Peo

Spp.	RD	RF	RBA	IVI
Trees				
<i>Cedrus deodara</i>	17.98	30.00	25.18	73.16
<i>Fraxinus micrantha</i>	6.74	30.00	0.60	37.34
<i>Pinus gerardiana</i>	74.16	30.00	73.69	177.85
<i>Pinus wallichiana</i>	1.12	10.00	0.54	11.66
	100	100	100	300
Shrubs				
<i>Berberis lycium</i>	10.37	10.61	15.77	36.75
<i>Caragana brevispora</i>	12.19	12.12	16.45	40.76
<i>Colutea nepalensis</i>	12.19	13.64	28.92	54.75
<i>Daphne oleoides</i>	14.02	12.12	5.62	31.77
<i>Desmodium triflorum</i>	13.41	12.12	2.96	28.49
<i>Lonicera quinquelocularis</i>	12.80	12.12	3.08	28.01
<i>Rhus cotinus</i>	15.85	15.15	24.27	55.28
<i>Rosa webbaiana</i>	9.15	12.12	2.93	24.19
	100	100	100	300
Herbs/grasses				
<i>Arenaria festucoides</i>	7.27	7.63	3.62	18.53
<i>Artemisia capillaris</i>	11.52	9.92	27.80	49.24
<i>Artemisia scoparia</i>	7.88	6.11	13.27	27.26
<i>Artemisia vulgaris</i>	6.67	6.12	18.59	31.36
<i>Astragalus candolleanus</i>	9.69	10.69	4.55	24.93
<i>Astragalus peduncularis</i>	6.67	8.39	3.09	18.16
<i>Bunium persicum</i>	5.45	5.34	4.31	15.11
<i>Chenopodium botrys</i>	7.27	6.87	11.05	25.19
<i>Cynoglossum wallichii</i>	6.06	5.34	1.21	12.61
<i>Myosotis sylvatica</i>	3.03	3.05	0.74	6.82
<i>Nepeta erecta</i>	3.64	3.05	0.67	7.35
<i>Origanum vulgare</i>	3.64	4.58	3.12	11.34
<i>Rumex nepalensis</i>	2.42	3.05	1.01	6.48
<i>Rheum webbianum</i>	6.06	6.11	2.56	14.73
<i>Salvia nubicola</i>	3.03	3.82	1.94	8.78
<i>Senecio kashmerianus</i>	3.03	3.82	0.64	7.49
<i>Swertia ciliata</i>	6.67	6.11	1.84	14.61
	100	100	100	300



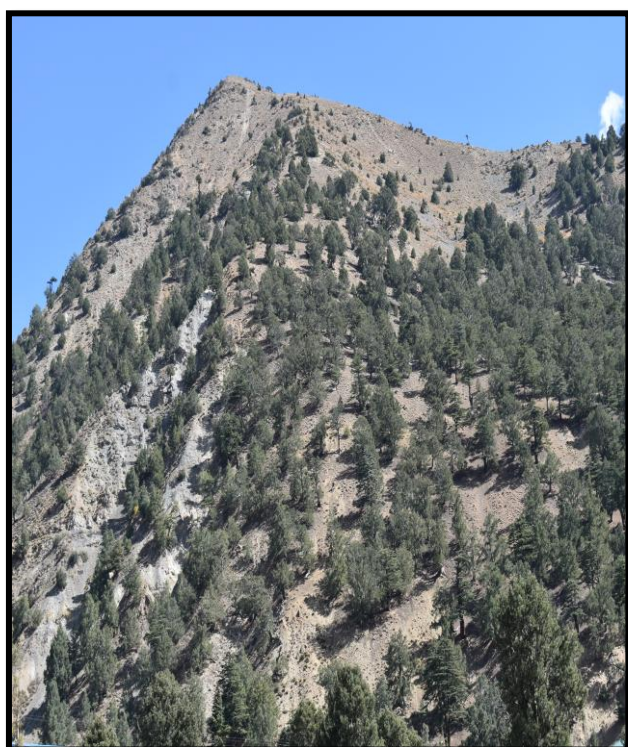
POOH



KALPA



KILBA



MOORANG

Plate 4. Phytosociological assessment of *Pinus gerardiana* in its natural habitat

4.2.4 Pooh Forest Range

The data collected in this range revealed the presence of three tree species, three shrub species, and nine herbaceous species. Among the tree species, *Pinus gerardiana* exhibited the highest dominance, with an IVI of 194.53, followed by *Cedrus deodara* (IVI: 75.81) and *Fraxinus micrantha* (IVI: 29.67), indicating its limited distribution. Among the shrubs, *Juniperus communis* had the highest IVI (162.50), signifying its dominance, followed by *Rosa webbaiana* (IVI: 85.19) and *Ephedra gerardiana* (IVI: 52.34) (Table 20). In the herbaceous layer, *Artemisia maritima* was the most dominant species (IVI: 66.11), followed by *Carpesium nepalense* (IVI: 53.29) and *Lactuca orientalis* (IVI: 46.97) (Kumar *et al.* 2019). The lowest IVI was recorded for *Myosotis sylvatica* (IVI: 11.69), indicating its minimal contribution to the vegetation structure, possibly due to niche specialization or competitive exclusion (Kumar *et al.* 2016). Understanding these dominance patterns is crucial for developing conservation strategies and sustainable management practices, particularly for economically valuable species like *Pinus gerardiana*. Ensuring the preservation of biodiversity and maintaining ecosystem balance requires targeted efforts to protect and sustainably utilize these species (Chauhan *et al.* 2025).

Table 20: Phytosociology of chilgoza pine forests in Pooh Forest Range of Kinnaur Forest Division, Reckong Peo

Spp.	RD	RF	RBA	IVI
Trees				
<i>Cedrus deodara</i>	9.28	37.50	29.03	75.81
<i>Fraxinus micrantha</i>	4.12	25.00	0.54	29.67
<i>Pinus gerardiana</i>	86.60	37.50	70.43	194.53
	100	100	100	300
Shrubs				
<i>Ephedra gerardiana</i>	20.42	28.13	3.79	52.34
<i>Juniperus communis</i>	38.03	34.40	90.06	162.50
<i>Rosa webbaiana</i>	41.50	37.50	6.15	85.19
	100	100	100	300
Herbs/grasses				
<i>Artemisia maritima</i>	14.84	12.63	38.64	66.11
<i>Astragalus peduncularis</i>	12.50	10.53	3.91	26.94
<i>Carpesium nepalense</i>	15.63	14.74	22.93	53.29
<i>Lactuca orientalis</i>	15.63	16.84	14.50	46.97
<i>Myosotis sylvatica</i>	5.47	5.26	0.96	11.69
<i>Nepeta erecta</i>	8.59	9.47	3.83	21.89
<i>Ranunculus hirtellus</i>	10.93	10.53	4.23	25.69
<i>Salvia nubicola</i>	5.47	7.37	4.33	17.17
<i>Thymus linearis</i>	10.94	12.63	6.66	30.24
	100	100	100	300

4.2.5 Pangi Forest Range

The data collected in this range revealed the presence of seven tree species, seven shrub species, and six herbaceous species (Table 21). Among the tree species, *Pinus gerardiana* exhibited the highest dominance, with an IVI value of 127.90, indicating its ecological significance in the region. This was followed by *Cedrus deodara* (IVI: 66.55) and *Pinus wallichiana* (IVI: 41.40). The lowest IVI values were recorded for *Juglans regia* (IVI: 7.18) and *Salix denticulata* (IVI: 15.03), suggesting their limited distribution in the area. Among the shrubs, *Berberis aristata* showed the highest dominance, with an IVI value of 68.46, followed by *Spiraea canescens* (IVI: 56.82) and *Rubus macrophyllus* (IVI: 49.73). The lowest IVI was recorded for *Aster albescens* (IVI: 11.00), indicating its relatively low ecological contribution to the shrub layer.

Table 21: Phytosociology of chilgoza pine forests in Pangi Forest Range of Chamba Forest Division, Reckong Peo

Spp.	RD	RF	RBA	IVI
Trees				
<i>Pinus gerardiana</i>	63.00	17.65	47.25	127.90
<i>Cedrus deodara</i>	18.00	17.65	30.90	66.55
<i>Pinus wallichiana</i>	9.00	17.65	14.75	41.40
<i>Acer acuminatum</i>	4.00	17.65	2.72	24.36
<i>Celtis australis</i>	3.00	11.76	2.81	17.58
<i>Juglans regia</i>	1.00	5.88	0.30	7.18
<i>Salix denticulata</i>	2.00	11.76	1.27	15.03
	100	100	100	300
Shrubs				
<i>Abelia biflora</i>	2.91	7.27	0.81	10.99
<i>Berberis aristata</i>	21.36	16.36	30.73	68.46
<i>Cotoneaster acuminatus</i>	15.53	14.55	5.87	35.95
<i>Cotoneaster obovata</i>	6.79	12.72	11.05	30.6
<i>Indigofera heterantha</i>	20.39	18.18	8.92	47.49
<i>Rubus macrophyllus</i>	14.56	18.18	16.98	49.73
<i>Spiraea canescens</i>	18.45	12.72	25.64	56.82
	100	100	100	300
Herbs/grasses				
<i>Artemisia maritima</i>	12.95	13.91	35.40	62.27
<i>Artemisia nilagirica</i>	15.83	14.78	36.71	67.32
<i>Carum carvi</i>	25.89	20.87	6.01	52.77
<i>Chaerophyllum reflexum</i>	15.83	18.26	4.25	38.33
<i>Thalictrum foliolosum</i>	14.39	14.78	6.24	35.41
<i>Verbascum thapsus</i>	15.11	17.39	11.39	43.89
	100	100	100	300

In the herbaceous layer, *Artemisia nilagarica* exhibited the highest IVI (67.32), followed closely by *Artemisia maritima* (IVI: 62.27) and *Carum carvi* (IVI: 52.77), suggesting their significant presence in the ecosystem. The lowest IVI values were recorded for *Thalictrum foliolosum* (IVI: 35.41) and *Chaerophyllum refexum* (IVI: 38.33), reflecting their relatively lower contribution to the vegetation composition. The dominance of *Pinus gerardiana* (IVI: 127.90) highlights its ecological adaptability and economic importance (Prakash *et al.* 2021). The significant presence of *Berberis aristata* and *Spiraea canescens* indicates their competitive advantage in shrub communities (Gupta *et al.* 2018; Kumar *et al.* 2019). The high IVI of *Artemisia nilagarica* and *Artemisia maritima* suggests their role in ecological succession and soil stabilization (Pandey and Rawat, 2023; Prakash *et al.* 2021).

4.2.6 Vegetation indices of trees, shrubs and herbs/grasses

The highest Shannon-Wiener diversity index (H) for trees was recorded in Pangi (1.18), followed by Kilba (1.02), while the lowest diversity was found in Kalpa (0.41). The Simpson dominance index (D) was highest in Kalpa (0.81), indicating that a few dominant species are more prevalent in this range. Conversely, the Simpson diversity index (1-D) was highest in Pangi (0.56), showing a more balanced species distribution. The Margalef species richness index (Dmg) also peaked in Pangi (1.30), indicating greater species richness in this region. Among shrubs, the highest Shannon-Wiener diversity index (H) was observed in Kilba (2.32), followed by Kalpa (2.12) and Moorang (2.07). The lowest diversity was recorded in Pooh (1.06). The Simpson dominance index (D) was highest in Pooh (0.36), suggesting the dominance of a few species in this range, while the lowest dominance was in Kilba (0.11). These findings are consistent with those reported by Kumar *et al.* 2016 and Prakash *et al.* 2021.

The Simpson diversity index (1-D) showed the highest value in Kilba (0.89), indicating a more evenly distributed shrub diversity. Herbs and grasses exhibited the highest species diversity in Moorang (H = 2.75), followed closely by Kalpa (2.76), while the lowest diversity was in Pangi (H = 1.76). The Simpson dominance index (D) was lowest in Kalpa and Moorang (0.07), showing lower dominance and higher evenness of species. The highest Simpson diversity index (1-D) was observed in Kalpa and Moorang (0.93), reinforcing their greater species heterogeneity (Table 22). The high species diversity in Pangi and Kilba suggests a more stable and resilient ecosystem, while the dominance of a few species in Kalpa indicates ecological imbalances (Kumar *et al.* 2016; Singh and Rawat, 2022). The greater evenness of shrubs in Kilba and herbs in Moorang and Kalpa highlights favorable habitat conditions promoting biodiversity (Bisht *et al.* 2022; Negi *et al.* 2022).

Table 22: Vegetation indices of trees, shrubs and herbs in different forest ranges of *Pinus gerardiana* forest of Himachal Pradesh

Diversity indices	Trees					Shrubs					Herbs				
	Kalpa	Kilba	Moorang	Pooh	Pangi	Kalpa	Kilba	Moorang	Pooh	Pangi	Kalpa	Kilba	Moorang	Pooh	Pangi
Shannon-Wiener diversity index (H)	0.41	1.02	0.76	0.48	1.18	2.12	2.32	2.07	1.06	1.85	2.76	2.57	2.75	2.14	1.76
Simpson dominance index (D)	0.81	0.48	0.59	0.76	0.44	0.13	0.11	0.13	0.36	0.17	0.07	0.08	0.07	0.12	0.18
Simpson diversity index (1-D)	0.19	0.53	0.41	0.24	0.56	0.87	0.89	0.87	0.64	0.83	0.93	0.92	0.93	0.88	0.82
Margalef species richness index (D_{mg})	0.49	0.88	0.67	0.44	1.30	1.59	1.99	1.37	0.40	1.31	3.05	2.49	3.13	1.65	1.01
Pielous Evenness Index (J)	0.37	0.63	0.55	0.43	0.60	0.96	0.97	0.99	0.96	0.95	0.98	0.97	0.97	0.97	0.98
Fisher's alpha diversity index (a)	0.67	1.12	0.86	0.59	1.71	2.08	2.72	1.76	0.54	1.72	4.52	3.52	4.76	2.21	1.28
Species heterogeneity (Hg)	0.90	0.69	0.77	0.87	0.66	0.36	0.33	0.36	0.60	0.41	0.26	0.29	0.26	0.35	0.42

4.2.7 Similarity indexes for trees

The highest similarity (1.00) was observed between Kalpa and Kilba, indicating nearly identical tree species composition in these two ranges. This was followed by Kilba and Moorang (0.89) and Kilba and Pangi (0.88), showing significant overlap in tree species between these sites. Moorang and Pangi exhibited a similarity of 0.92, suggesting a closely related species distribution (Table 23). However, the lowest similarity was found between Kalpa and Pooh (0.73), indicating distinct vegetation composition in these ranges. Similarly, the Kalpa-Moorang similarity (0.79) was relatively lower than other comparisons, suggesting some variation in species distribution. The high similarity between Kalpa and Kilba suggests shared ecological conditions and habitat continuity, while the lower similarity between Kalpa and Pooh indicates distinct environmental factors influencing species composition (Rikhari *et al.* 1997; Kumar *et al.* 2016; Prakash *et al.* 2021).

Table 23: Similarity index for trees in different forest range of *Pinus gerardiana* forest of Himachal Pradesh

S. No.	Sites	Kalpa	Kilba	Moorang	Pooh	Pangi
1.	Kalpa	1.00				
2.	Kilba	0.90	1.00			
3.	Moorang	0.79	0.89	1.00		
4.	Pooh	0.73	0.84	0.85	1.00	
5.	Pangi	0.78	0.88	0.92	0.83	1.00

4.2.8 Similarity indexes for shrubs

The highest similarity (1.00) was observed between Kalpa and itself, followed by Kalpa and Pangi (0.89), and Moorang and Kalpa (0.88), indicating a significant overlap in tree species among these ranges. Similarly, Pangi and Pooh exhibited a similarity of 0.92, suggesting a strong relationship in species composition (Table 24). On the other hand, the lowest similarity was recorded between Kilba and Pooh (0.34), indicating considerable differences in tree species composition between these sites. Additionally, Moorang and Pooh had a relatively low similarity value of 0.41, further highlighting distinct vegetation differences in these ranges. A comparable level of dominance among shrub and grass species was also observed in earlier vegetation studies conducted by Sharma (2004) and Anonymous (1991).

Table 24: Similarity index for shrubs in different forest range of *Pinus gerardiana* forest of Himachal Pradesh

S. No.	Sites	Kalpa	Kilba	Moorang	Pooh	Pangi
1.	Kalpa	1				
2.	Kilba	0.79	1.00			
3.	Moorang	0.88	0.76	1.00		
4.	Pooh	0.77	0.34	0.41	1	
5.	Pangi	0.89	0.77	0.82	0.92	1

4.2.9 Similarity indexes for herbs/grasses

The highest similarity (1.00) was observed between Kalpa and itself, followed by Moorang and Kalpa (0.97), and Pangi and Pooh (0.97), suggesting a significant overlap in herb species composition among these ranges. Similarly, Kilba and Pooh exhibited a similarity of 0.91, indicating a relatively high degree of shared species. On the other hand, the lowest similarity was recorded between Kalpa and Pangi (0.60), indicating substantial differences in herb species composition. Additionally, Kilba and Moorang had a relatively low similarity value of 0.77, further highlighting variations in herbaceous vegetation between these sites (Table 25). These findings are consistent with those reported by several other researchers, including Kumar *et al.* (2016) and Prakash *et al.* (2021).

Table 25: Similarity index for herbs in different forest range of *Pinus gerardiana* forest of Himachal Pradesh

S. No.	Sites	Kalpa	Kilba	Moorang	Pooh	Pangi
1.	Kalpa	1				
2.	Kilba	0.83	1			
3.	Moorang	0.97	0.77	1		
4.	Pooh	0.81	0.91	0.79	1	
5.	Pangi	0.60	0.82	0.89	0.97	1

4.3.1 Natural regeneration and soil nutrient interactions

4.3.1 Kalpa Forest Range

The results revealed that *Pinus gerardiana* exhibited the highest number of recruits (333.33 ha⁻¹), followed by *Pinus wallichiana* (250.00 ha⁻¹) and *Cedrus deodara* (125.00 ha⁻¹). However, the establishment success varied among species. *Pinus gerardiana* showed the highest establishment stocking (10.50%) and regeneration success (14.17 %), indicating better survival and recruitment potential compared to other species. *Cedrus deodara* had a lower establishment stocking (5.31 %), while *Pinus wallichiana* recorded the regeneration success (12.50%) (Table 26). Malik (2007) reported the highest number of recruits (812.5), unestablished regeneration (341.66), and established regeneration (291.66) on the left (western) aspect of the Sutlej River compared to the right bank (eastern aspect). These findings align with those of Malik *et al.* 2012 and Kumar *et al.* 2015.

Table 26: Regeneration dynamics of tree species in *Pinus gerardiana* forest of Kalpa Forest Range in Kinnaur (H.P)

S. No.	Tree spp.	Recruits ha ⁻¹	Unestablished ha ⁻¹	Established ha ⁻¹	Establishment stocking (%)	Regeneration success (%)
1.	<i>Pinus gerardiana</i>	333.33	416.67	250.00	10.50	14.17
2.	<i>Cedrus deodara</i>	125.00	375.00	230.00	5.31	13.75
3.	<i>Pinus wallichiana</i>	250.00	250.00	218.11	10.00	12.50
Total		1375.00	1041.67	698.11	23.81	40.42

4.3.2 Kilba Forest Range

The results revealed that *Pinus gerardiana* exhibited the highest number of recruits (416.67 ha⁻¹), followed by *Quercus ilex* (333.33 ha⁻¹) and *Cedrus deodara* (250.00 ha⁻¹). However, the establishment success varied among species (Table 27). *Quercus ilex* recorded the highest establishment stocking (12.60%) and regeneration success (16.67%), indicating relatively better survival compared to other species. *Pinus gerardiana* had a lower establishment stocking 8.94 per cent and *Cedrus deodara* exhibited the lowest regeneration success (11.25%). These findings align with those of Peltier and Dauffy (2009).

Table 27: Regeneration dynamics of tree species in *Pinus gerardiana* forest of Kilba Forest Range in Kinnaur (H.P)

S. No.	Tree spp.	Recruits ha ⁻¹	Unestablished ha ⁻¹	Established ha ⁻¹	Establishment stocking (%)	Regeneration success (%)
1.	<i>Pinus gerardiana</i>	416.67	500.00	280.00	8.94	15.00
2.	<i>Cedrus deodara</i>	250.00	125.00	260.22	10.00	11.25
3.	<i>Quercus ilex</i>	333.33	333.33	388.44	12.60	16.67
Total		1000.00	958.33	928.66	31.55	42.92

4.3.3 Moorang Forest Range

The results revealed that *Pinus gerardiana* exhibited the highest number of recruits (500.00 ha⁻¹), followed by *Cedrus deodara* (375.00 ha⁻¹). However, the establishment success varied between species. *Pinus gerardiana* recorded the highest establishment stocking (6.04%) and regeneration success (19.17%), indicating better survival and recruitment potential (Table 28). In contrast, *Cedrus deodara* had a lower establishment stocking (5.00%) but showed a relatively high regeneration success (11.25%). Similar observations have been reported by Singh *et al.* (1973) and Tandon (1963).

Table 28: Regeneration dynamics of tree species in *Pinus gerardiana* forest of Moorang Forest Range in Kinnaur (H.P)

S. No.	Tree spp.	Recruits ha ⁻¹	Unestablished ha ⁻¹	Established ha ⁻¹	Establishment stocking (%)	Regeneration success (%)
1.	<i>Pinus gerardiana</i>	500.00	583.33	333.33	6.04	19.17
2.	<i>Cedrus deodara</i>	375.00	250.00	250.00	5.00	11.25
Total		875.00	833.33	583.33	11.04	30.42

4.3.4 Pooh Forest Range

The results revealed that *Pinus gerardiana* recorded the highest number of recruits (248.22 ha⁻¹), followed by *Cedrus deodara* (218.22 ha⁻¹). However, the establishment success varied between species. *Pinus gerardiana* showed a higher establishment stocking (6.11%) and regeneration success

(10.00%) compared to *Cedrus deodara*, which had an establishment stocking of 5.22 per cent and regeneration success of 9.50 per cent (Table 29). The results are supported by the studies of Glover (1937), Reddy (1963), Ahmed and Latif (2007), and Sharma *et al.* (2010) on the natural regeneration of Chilgoza pine in its native habitat.

Table 29: Regeneration dynamics of tree species in *Pinus gerardiana* forest of Pooh Forest Range in Kinnaur (H.P)

S. No.	Tree spp.	Recruits ha ⁻¹	Unestablished ha ⁻¹	Established ha ⁻¹	Establishment stocking (%)	Regeneration success (%)
1.	<i>Pinus gerardiana</i>	248.22	318.22	158.22	6.11	10.00
2.	<i>Cedrus deodara</i>	218.22	238.22	148.44	5.22	9.50
Total		466.44	556.44	306.66	11.33	19.50

4.3.5 Pangi Forest Range

The results revealed (Table 30) that *Pinus gerardiana* recorded the highest number of recruits (520.22 ha⁻¹), followed closely by *Cedrus deodara* (500.00 ha⁻¹) and *Pinus wallichiana* (416.67 ha⁻¹). In contrast, *Acer acuminatum* (250.00 ha⁻¹) and *Celtis australis* (125.00 ha⁻¹) showed comparatively lower recruitment densities. In terms of establishment success, *Pinus gerardiana* exhibited the highest establishment stocking (10.39%) along with a regeneration success rate of 15.83 per cent, reflecting its relatively strong regeneration performance. *Cedrus deodara* followed with an establishment stocking of 6.07 per cent and the highest regeneration success among all species (25.83%), indicating effective seedling establishment despite moderate spatial distribution. *Pinus wallichiana* showed an establishment stocking of 9.58 per cent and regeneration success of 11.67 per cent, while *Acer acuminatum* had both establishment stocking and regeneration success at 10.00 per cent, highlighting successful conversion of all recruits to established individuals. On the other hand, *Celtis australis* recorded the lowest values for both establishment stocking (4.53%) and regeneration success (6.25%), suggesting poor regeneration potential. Similar observations have been reported by Singh *et al.* (1973) and Prakash *et al.* 2021.

Table 30: Regeneration dynamics of tree species in *Pinus gerardiana* forest of Pangi Forest Range in Chamba (H.P)

S. No.	Tree spp.	Recruits ha ⁻¹	Unestablished ha ⁻¹	Established ha ⁻¹	Establishment stocking (%)	Regeneration success (%)
1.	<i>Pinus gerardiana</i>	520.22	583.33	250.00	10.39	15.83
2.	<i>Cedrus deodara</i>	500.00	916.67	416.67	6.07	25.83
3.	<i>Pinus wallichiana</i>	416.67	166.67	250.00	9.58	11.67
4.	<i>Celtis australis</i>	125.00	125.00	125.00	4.53	6.25
5.	<i>Acer acuminatum</i>	250.00	0.00	250.00	10.00	10.00
Total		2041.66	1791.67	1291.67	38.58	69.58



Plate 5. Natural Regeneration and soil nutrient dynamics of *Pinus gerardiana*

4.3.6 Soil macronutrients status

Pinus gerardiana forests in Kilba recorded the highest mean available nitrogen ($204.40 \text{ kg ha}^{-1}$), followed by Moorang ($195.20 \text{ kg ha}^{-1}$) and Kalpa ($194.40 \text{ kg ha}^{-1}$). The lowest mean nitrogen availability was observed in Pooh ($171.90 \text{ kg ha}^{-1}$). Across all sites, nitrogen content decreased with increasing soil depth, with the highest values in the 0–20 cm layer and the lowest in the 40–60 cm layer. The overall mean nitrogen content across depths was $238.70 \text{ kg ha}^{-1}$ (0–20 cm), $186.30 \text{ kg ha}^{-1}$ (20–40 cm), and $146.60 \text{ kg ha}^{-1}$ (40–60 cm). The highest mean available phosphorus was recorded in Kalpa (22.70 kg ha^{-1}), followed by Pangl (21.10 kg ha^{-1}) and Kilba and Moorang (20.90 kg ha^{-1} each). Pooh had the lowest phosphorus availability (19.50 kg ha^{-1}). Like nitrogen, phosphorus levels declined with increasing soil depth, with the overall mean values being 25.30 kg ha^{-1} (0–20 cm), 20.30 kg ha^{-1} (20–40 cm), and 17.60 kg ha^{-1} (40–60 cm) (Table 31). The highest mean available potassium was observed in Kalpa ($483.50 \text{ kg ha}^{-1}$), followed by Pangl ($481.50 \text{ kg ha}^{-1}$), while the lowest was in Pooh ($413.40 \text{ kg ha}^{-1}$). Potassium content also decreased with depth, with mean values of $528.10 \text{ kg ha}^{-1}$ (0–20 cm), $455.10 \text{ kg ha}^{-1}$ (20–40 cm), and $372.90 \text{ kg ha}^{-1}$ (40–60 cm) across all sites. Organic carbon content was highest in the surface layer (0–20 cm) and decreased with depth. The highest mean organic carbon was recorded in Pooh (1.16%), followed by Moorang (1.15%) and Kilba (1.14%). The lowest was observed in Kalpa and Pangl (1.12% each). The overall mean values across depths were 1.30 per cent (0–20 cm), 1.09 per cent (20–40 cm), and 0.85 per cent (40–60 cm). Almost similar results and variations have been reported by Singh (2004) in deodar, Kumar *et al.* 2017 and Tapwal *et al.* (2023) in chilgoza pine.

4.3.7 Soil physicochemical properties

The results revealed variations in soil physicochemical properties across different sites and depths. Soil pH varied across sites and depths, with values ranging from 6.23 to 6.68. The highest mean pH was recorded in Pooh (6.51), followed by Moorang and Pangl (6.49 each), while the lowest was in Kalpa (6.41). Soil pH increased with depth, with overall mean values of 6.32 (0–20 cm), 6.48 (20–40 cm), and 6.62 (40–60 cm). Bulk density increased with depth across all sites, indicating soil compaction at lower depths. The highest mean bulk density was observed in Pangl (1.37 g cm^{-3}), while the lowest was in Kilba (1.33 g cm^{-3}). The overall mean values across depths were 1.27 g cm^{-3} (0–20 cm), 1.33 g cm^{-3} (20–40 cm), and 1.44 g cm^{-3} (40–60 cm). Electrical conductivity (EC) declined with depth, with the highest values recorded in the 0–20 cm layer. The highest mean EC was observed in Pangl (0.20 dS m^{-1}), followed by Pooh and Moorang (0.19 dS m^{-1} each). The lowest was recorded in Kalpa (0.17 dS m^{-1}). The overall mean values across depths were 0.22 dS m^{-1} (0–20 cm), 0.18 dS m^{-1} (20–40 cm), and 0.16 dS m^{-1} (40–60 cm). Soil moisture content was highest in the top layer (0–20 cm) and declined with depth. The highest mean soil moisture was recorded in Kalpa (31.97%), followed by Moorang (31.57%), while the lowest was in Pooh (28.74%). The overall mean values across depths were 32.48 per cent (0–20 cm), 30.82 per cent (20–40 cm), and 28.59 per cent (40–60 cm) (Table 32). Almost similar results and variations have been reported by Singh (2004) in deodar, Sharma (2006) in fir and spruce, Mahajan (2010) in chir pine.

Table 31: Soil macronutrients status of different forest range of chilgoza pine forest in Himachal Pradesh

Site	Available N (kg ha ⁻¹)			Mean	Available P (kg ha ⁻¹)			Mean	Available K (kg ha ⁻¹)			Mean	Organic Carbon (%)			Mean	
	D1	D2	D3		D1	D2	D3		D1	D2	D3		D1	D2	D3		
	0-20 (cm)	20-40 (cm)	40-60 (cm)		0-20 (cm)	20-40 (cm)	40-60 (cm)		0-20 (cm)	20-40 (cm)	40-60 (cm)		0-20 (cm)	20-40 (cm)	40-60 (cm)		
Kalpa	242.80	192.50	147.90	194.40	27.40	21.70	19.00	22.70	564.50	481.00	404.80	483.50	1.40	1.08	0.85	1.12	
Kilba	259.30	195.00	159.10	204.40	25.00	20.80	17.00	20.90	521.20	427.50	367.40	438.80	1.40	1.11	0.91	1.14	
Moorang	239.70	195.90	149.90	195.20	24.80	20.10	17.90	20.90	514.60	454.40	359.60	442.90	1.40	1.15	0.92	1.15	
Pooh	220.90	166.10	128.80	171.90	23.60	18.70	16.20	19.50	503.60	430.60	306.10	413.40	1.30	1.20	0.93	1.16	
Pangi	230.60	181.80	147.20	186.60	25.40	20.00	18.00	21.10	536.50	481.80	426.20	481.50	1.40	1.14	0.90	1.12	
Mean	238.70	186.30	146.60		25.30	20.30	17.60		528.10	455.10	372.90		1.30	1.09	0.85		
CD	D: Depth 18.62 S: Site N/A D X S: Depth X Site N/A				CD	D: Depth 0.99 S: Site 1.28 D X S: Depth X Site N/A				CD	D: Depth 22.98 S: Site 29.67 D X S: Depth X Site N/A			CD	D: Depth 0.11 S: Site N/A D X S: Depth X Site N/A		

*N: Nitrogen; P: Phosphorus; K: Potassium

Table 32: Soil physicochemical properties of different forest range of chilgoza pine forest in Himachal Pradesh

Site	pH			Mean	Bulk Density (g cm ⁻³)			Mean	Electrical Conductivity (d Sm ⁻¹)			Mean	Soil Moisture Content (%)			Mean
	D1	D2	D3		D1	D2	D3		D1	D2	D3		D1	D2	D3	
	0-20 (cm)	20-40 (cm)	40-60 (cm)		0-20 (cm)	20-40 (cm)	40-60 (cm)		0-20 (cm)	20-40 (cm)	40-60 (cm)		0-20 (cm)	20-40 (cm)	40-60 (cm)	
Kalpa	6.23	6.43	6.58	6.41	1.25	1.32	1.44	1.34	0.20	0.17	0.15	0.17	33.52	32.08	30.30	31.97
Kilba	6.31	6.45	6.58	6.45	1.27	1.30	1.42	1.33	0.21	0.18	0.15	0.18	30.79	29.78	27.52	29.36
Moorang	6.33	6.47	6.68	6.49	1.28	1.34	1.43	1.35	0.22	0.18	0.16	0.19	33.47	31.83	29.42	31.57
Pooh	6.35	6.54	6.62	6.51	1.26	1.34	1.45	1.35	0.23	0.19	0.16	0.19	30.90	28.50	26.83	28.74
Pangi	6.38	6.49	6.61	6.49	1.29	1.34	1.46	1.37	0.24	0.19	0.17	0.20	33.70	31.90	28.90	31.49
Mean	6.32	6.48	6.62		1.27	1.33	1.44		0.22	0.18	0.16		32.48	30.82	28.59	
CD	D: Depth 0.04 S: Site 0.05 D X S: Depth X Site N/A				CD	D: Depth 0.03 S: Site N/A D X S: Depth X Site N/A			CD	D: Depth 0.006 S: Site 0.007 D X S: Depth X Site N/A			CD	D: Depth 1.05 S: Site 1.35 D X S: Depth X Site N/A		

To study the socio-economic status of chilgoza nut collectors.

4.4.1. Size and structure of family:

The family size, structure, workforce distribution, and literacy levels are crucial factors influencing household socio-economic conditions, particularly in resource-dependent activities. Table 33 presents the socio-demographic profile of the 60 sampled households, categorized into 25 marginal, 22 small, and 13 medium-sized families. A review of the table indicates that the overall average family size was 6.15 persons per household. Among them, males constituted 42.00 per cent of the total population, while females accounted for 38.54 per cent. Children formed 19.46 per cent of the family members, with male children comprising 11.79 per cent and female children 9.64 per cent. Family size varied across different categories, with marginal families having the smallest average size (5.75 members) and medium families the largest (7.20 members). The prevalence of joint families was notable across all groups, ranging from 54.55 per cent to 72.00 per cent. At an overall level, 65.00 per cent of families followed a joint structure, while 35.00 per cent were nuclear households.

Table 33: Demographic profile of sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Type of family				
Joint	18 (72.00)	12 (54.55)	9 (69.23)	39 (65.00)
Nuclear	7 (28.00)	10 (45.45)	4 (30.77)	21 (35.00)
Average family size	5.75	6.45	7.20	6.15
Male	2.50 (43.48)	2.60 (40.31)	3.00 (41.67)	2.70 (42.00)
Female	2.10 (36.52)	2.45 (37.98)	2.55 (35.42)	2.37 (38.54)
Children	1.15 (20.00)	1.40 (21.71)	1.65 (22.91)	1.38 (19.46)
Male	0.60 (10.43)	0.85 (13.20)	0.80 (11.11)	0.75 (11.79)
Female	0.55 (9.57)	0.55 (8.51)	0.85 (11.80)	0.63 (9.64)

4.4.2. Literacy status

The educational status of the sampled households was analyzed, and the findings are presented in Table 34. The data indicates that the overall literacy rate stood at 83.8 per cent, with variations across different farm categories ranging from 78.1 per cent to 89 per cent. A gender-wise analysis reveals that the literacy rate among males was significantly higher at 89.2 per cent, fluctuating between 85.75 per cent in marginal households and 92.85 per cent in small farm households. In contrast, the female literacy rate was comparatively lower at 78.8 per cent, varying from 70.2 per cent in marginal households to 85 per cent in small farm households. The literacy index, which measures the level of education attained, was also examined. It was found to be highest in small farm households (3.35), followed by medium (3.15) and marginal (2.7) households. A closer look at different education levels indicates that a higher percentage of individuals attained education up to the intermediate and graduate levels, with 25.92 per cent of the total population falling in the intermediate category and 16.75 per cent having completed graduation. However, post-graduation attainment remained relatively low, with only 4 per cent of individuals holding postgraduate degrees.

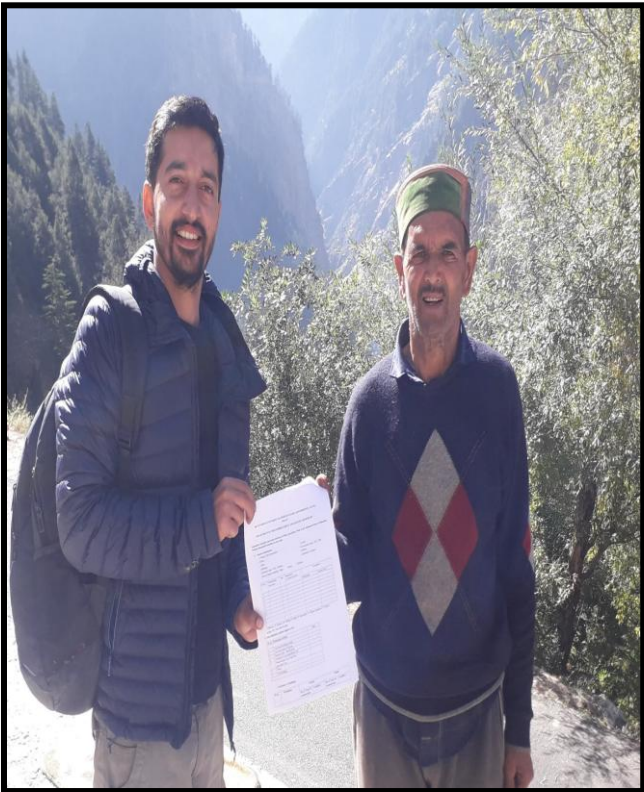


Plate 6. Socio-economic survey of chilgoza nut collectors

Table 34: Literacy status of the sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal (Male)	Marginal (Female)	Marginal (Total)	Small (Male)	Small (Female)	Small (Total)	Medium (Male)	Medium (Female)	Medium (Total)	Overall (Male)	Overall (Female)	Overall (Total)
Illiterate	12.5	28.3	20.4	8.9	14.2	11.55	10.75	18.25	14.5	10.05	20.12	15.08
Primary	8.2	7.15	7.68	7.05	8.8	7.92	6.5	15	10.75	7.25	9.85	8.55
Middle	10.5	16.7	13.6	5.85	12	8.92	8.2	7.25	7.72	8	11.85	9.92
Matric	12.3	15.4	13.9	12.75	13.85	13.3	16.5	11.9	14.2	13.55	13.4	13.47
Intermediate	28.1	18.4	23.25	27.8	28.5	28.15	18	30.25	24.12	25.85	26	25.92
Graduate	16.25	9.3	12.78	30.5	10.5	20.5	22.5	8	15.25	23.75	9.75	16.75
Post graduate	4.5	2.1	3.3	5.2	3.15	4.2	8	0	4	5.85	2.15	4
Non-school going	7.65	2.65	5.15	6.45	4	5.22	7.55	9.35	8.45	7.2	5.85	6.52
Total	100	100	100	100	100	100	100	100	100	100	100	100
Literacy rate	85.75	70.2	78.1	92.85	85	89	88.15	80.65	84.4	89.2	78.8	83.8
Literacy index	3.15	2.25	2.7	3.75	2.9	3.35						

4.4.3. Occupational distribution

The occupational structure of the selected households was analysed to determine the workforce distribution across agriculture, allied sectors, and non-farm activities. The per-household occupational structure is presented in Table 35. The data clearly indicates that agriculture was the predominant occupation in the study area, with 76.75 per cent of the workforce engaged in farming at the overall level. Across different farm categories, the proportion of households practicing agriculture ranged from 74.35 per cent in marginal farms to 78.25 per cent in medium farms. Besides agriculture, a section of the population was found to be involved in additional occupations. About 5.08 per cent of individuals combined agriculture with business, while 6.45 per cent engaged in both agriculture and service. Among non-farm occupations, public sector employment (5.26%) was more preferred than private sector jobs (4.07%). Business, on the other hand, accounted for a small share of the workforce, with only 2.39 per cent engaged in business activities.

Table 35: Farm category wise occupational distributions of the sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Agriculture	2.85 (74.35)	3.50 (76.25)	4.00 (78.25)	3.30 (76.75)
Business	0.06 (1.56)	0.08 (1.83)	0.20 (4.07)	0.10 (2.39)
Public sector	0.10 (2.61)	0.30 (6.89)	0.25 (5.08)	0.22 (5.26)
Private sector	0.14 (3.65)	0.11 (2.02)	0.26 (5.29)	0.17 (4.07)
Agriculture + business	0.30 (8.05)	0.25 (5.72)	0.18 (3.66)	0.25 (5.08)
Agriculture + service	0.38 (9.78)	0.32 (7.34)	0.18 (3.66)	0.29 (6.45)
Total	3.83 (100)	4.56 (100)	5.12 (100)	4.33 (100)

4.4.4. Work Force

The workforce availability and dependency ratio play a crucial role in determining the economic stability of households. Table 36 presents the distribution of workers and dependents among different farm categories. At the overall level, the average number of workers per household was found to be 4.30, accounting for 66.00 per cent of the total family members. Across different farm categories, the number of workers varied, ranging from 3.75 in marginal households to 5.10 in medium households. Dependents, including children below 14 years, individuals above 14 who are not earning, and elderly members above 65 years who are not engaged in economic activities, comprised 34.00 per cent of the total family members. The average number of dependents per household was recorded as 2.22 at the overall level, with small farms having the highest number of dependents (2.42) and marginal farms the lowest (1.75).

The dependency ratio, which indicates the burden of non-working members on the working population, was found to be 0.51 when calculated with respect to workers and 0.34 when calculated concerning family size. Among different categories, the dependency ratio concerning workers ranged between 0.47 (marginal households) and 0.54 (small households), while in relation to family size, it remained relatively stable across all categories, ranging between 0.32 and 0.35.

Table 36: Farm category wise distribution of workers and dependents of the sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Average no. of workers	3.75 (68.20)	4.50 (65.10)	5.10 (66.90)	4.30 (66.00)
Less than 14	0.92 (16.73)	1.38 (19.85)	1.60 (20.75)	1.30 (19.25)
Above 14 not earning	0.42 (7.63)	0.66 (9.55)	0.50 (6.56)	0.52 (7.95)
Above 65 not earning	0.55 (9.95)	0.44 (6.38)	0.75 (9.84)	0.55 (8.45)
Average no. of dependents	1.75 (31.80)	2.42 (34.90)	2.65 (33.10)	2.22 (34.00)
Average family size	5.5	6.92	7.75	6.55
Dependency Ratio w.r.t Workers	0.47	0.54	0.52	0.51
Dependency ratio w.r.t family size	0.32	0.35	0.34	0.34

4.4.5. Farm Workers

The gender-wise distribution of farm workers in the study area is presented in Table 37. The data indicates that, at an overall level, the average number of farm workers per household was 3.98. The number of farm workers varied across different farm categories, ranging from 3.7 in marginal households to 4.3 in medium households. In terms of gender distribution, males constituted 49.75 per cent of the total farm workers at the overall level, while females accounted for 50.25 per cent. The proportion of male farm workers varied between 46.25 per cent in small farms and 52.00 per cent in marginal farms, while the percentage of female farm workers ranged from 48.00 per cent in marginal farms to 53.75 per cent in small farms.

Table 37: Gender wise distribution of the farm workers in sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Male	1.92 (52.00)	1.94 (46.25)	2.20 (51.25)	1.98 (49.75)
Female	1.78 (48.00)	2.26 (53.75)	2.10 (48.75)	2.00 (50.25)
Average number of farm workers	3.7	4.2	4.3	3.98

4.4.6. Land use pattern

Land use pattern determines the type of farming system in an area. The farm category-wise land use pattern of the sampled farmers has been presented in Table 38. The average size of landholding at the overall

level was found to be 1.49 ha⁻¹. Out of this, 70.30 per cent of the total land was cultivated, which included 52.30 per cent under orchards and 19.58 per cent under crops. The total irrigated cultivated area accounted for 68.20 per cent of the total land. At the overall level, forest land covered 17.50 per cent of the total area, 8.39 per cent of the land was used as ghasnis/pastures, 5.59 per cent was uncultivated/waste land, and 4.90 per cent was classified as land put to non-agricultural use, which included roads, footpaths, buildings, etc. The average landholding for marginal, small, and medium farms was found to be 0.65, 1.48, and 3.01 ha⁻¹, respectively. The total cultivated area varied between 58.20 per cent for medium farms to 85.00 per cent for marginal farms, while the irrigated area ranged from 57.91 per cent in medium farms to 81.50 per cent in marginal farms.

The area under orchards was the highest for marginal farmers (58.00%), followed by small (55.20%) and medium (45.00%) farmers. All the orchard areas were irrigated. The forest land was found to be highest in medium farms (26.93%), followed by small (10.35%) and marginal farms (4.90%).

Table 38: Farm category wise land use pattern of sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Cultivated area				
Total cultivated area	0.55 (85.00)	1.10 (74.50)	1.75 (58.20)	1.05 (70.30)
Irrigated	0.53 (81.50)	1.07 (72.00)	1.72 (57.91)	1.02 (68.20)
Unirrigated	0.02 (3.50)	0.03 (2.50)	0.03 (0.99)	0.03 (2.10)
Orchard area				
Total orchard area	0.38 (58.00)	0.80 (55.20)	1.35 (45.00)	0.75 (52.30)
Irrigated	0.38 (58.00)	0.80 (55.20)	1.35 (45.00)	0.75 (52.30)
Unirrigated	-	-	-	-
Area under crops				
Total area under crops	0.18 (27.50)	0.30 (20.10)	0.42 (14.15)	0.28 (19.58)
Irrigated	0.17 (26.00)	0.27 (18.20)	0.40 (13.47)	0.26 (18.18)
Unirrigated	0.01 (1.50)	0.03 (1.90)	0.02 (0.68)	0.02 (1.40)
Forest land	0.03 (4.90)	0.15 (10.35)	0.80 (26.93)	0.25 (17.50)
Ghasnis/ pasture land	0.02 (3.50)	0.10 (6.90)	0.30 (10.10)	0.12 (8.39)
Uncultivated/ waste land	0.01 (1.50)	0.11 (7.60)	0.18 (5.90)	0.08 (5.59)
Land put to non-agricultural use	0.05 (7.60)	0.09 (6.20)	0.10 (3.37)	0.07 (4.90)
Total land	0.65 (100.00)	1.48 (100.00)	3.01 (100.00)	1.49 (100.00)

4.4.7. Cropping pattern

Cropping patterns and intensity reflect the agricultural diversity and land utilization efficiency in a region. The farm category-wise cropping pattern of the sampled farmers is presented in Table 39. The overall gross cropped area was found to be 1.24 ha⁻¹, with a net sown area of 1.05 ha⁻¹, resulting in an overall cropping intensity of 118.10 per cent. Cropping intensity was highest among marginal farms (130.91%), followed by small (121.82%) and medium farms (117.71%). Among the Kharif crops, rajma was the most widely cultivated crop, occupying 9.80 per cent of the gross cropped area at the overall level. Other crops like maize (3.90%), ogla (1.45%), phafra (1.00%), koda (1.00%), potato (1.80%), and mash (1.85%) were also grown. The area under vegetables was highest for small farms (2.65%), while it remained low in marginal (0.70%) and medium farms (0.50%). In the Rabi season, barley was the dominant crop, covering 13.35 per cent of the gross cropped area, followed by wheat (3.95%). The area under pea cultivation was found to be very small (0.70%) at the overall level. During the Zaid season, pea was cultivated across different farm categories, covering 2.50 per cent of the gross cropped area at the overall level. The orchard area constituted 58.80 per cent of the gross cropped area, indicating a strong focus on horticulture. The proportion of orchard area increased with farm size, accounting for 51.00 per cent in marginal farms, 58.00 per cent in small farms, and 61.00 per cent in medium farms. The findings suggest that while food crops like barley, wheat, and rajma are important, horticultural activities dominate the land use pattern in the study area.

Table 39: Farm category wise cropping pattern of the sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Kharif				
Rajma	0.090 (10.50)	0.125 (8.30)	0.190 (9.10)	0.123 (9.80)
Ogla	0.015 (2.10)	0.018 (1.35)	0.025 (1.20)	0.018 (1.45)
Phafra	0.007 (1.00)	0.015 (1.15)	0.019 (0.90)	0.012 (1.00)
Koda	0.009 (1.30)	0.016 (1.20)	0.012 (0.60)	0.012 (1.00)
Maize	0.030 (4.10)	0.050 (3.80)	0.085 (4.20)	0.048 (3.90)
Potato	0.012 (1.65)	0.030 (2.30)	0.028 (1.35)	0.022 (1.80)
Mash	0.018 (2.50)	0.022 (1.65)	0.033 (1.60)	0.023 (1.85)
Vegetables	0.005 (0.70)	0.035 (2.65)	0.010 (0.50)	0.017 (1.40)
Rabi				
Wheat	0.028 (3.90)	0.050 (3.80)	0.085 (4.10)	0.048 (3.95)
Barley	0.130 (17.90)	0.175 (13.25)	0.270 (12.90)	0.175 (13.35)
Pea	0.003 (0.40)	0.020 (1.50)	-	0.008 (0.70)
Zaid				
Pea	0.025 (3.50)	0.022 (1.65)	0.060 (2.85)	0.030 (2.50)
Orchard Area	0.375 (51.00)	0.80 (58.00)	1.300 (61.00)	0.730 (58.80)
Gross Cropped Area	0.740 (100)	1.340 (100)	2.060 (100)	1.240 (100)
Net Sown Area	0.55	1.1	1.75	1.05
Cropping Intensity (%)	130.91	121.82	117.71	118.1

4.4.8. Livestock inventory

Livestock plays a crucial role in hill agriculture by providing milk, animal products, and farmyard manure (FYM). Table 40 presents the livestock inventory across different farm categories, highlighting variations in livestock ownership among marginal, small, and medium farmers. At the overall level, cattle were the most preferred livestock, with an average of 2.25 adult cattle units per farm, ranging from 1.55 units in marginal farms to 3.50 units in medium farms. Among cattle, crossbred cows were preferred over local cows, constituting 1.22 units per farm overall. The proportion of local cows was slightly higher in small farms (0.90 units) compared to marginal (0.54 units) and medium farms (1.30 units). Goats and sheep were also reared in the study area. Sheep were more prevalent among small farmers (0.98 units), followed by medium (1.30 units) and marginal farmers (0.45 units). Goats were found more in medium farms (0.45 units), while their presence was lower in marginal (0.11 units) and small farms (0.04 units). Among goats and sheep, adult animals dominated over young ones (kids and lambs). Horses, donkeys, and mules were exclusively owned by medium farmers (0.25 units), indicating their role in transportation or load-bearing activities in larger farms.

The findings indicate a positive relationship between landholding size and livestock ownership, as medium farmers maintained the highest number of livestock (5.50 ACU), followed by small (3.30 ACU) and marginal farmers (2.10 ACU).

Table 40: Average livestock inventory on different categories of farm in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Cattle	70.45 (1.55)	65.78 (2.30)	60.12 (3.50)	65.12 (2.25)
Local cow	24.50 (0.54)	25.75 (0.90)	21.45 (1.30)	23.90 (0.85)
Cross bred	38.00 (0.85)	37.00 (1.28)	32.75 (1.90)	35.58 (1.22)
Young one	7.95 (0.17)	3.03 (0.10)	5.92 (0.40)	5.63 (0.19)
Goats	5.20 (0.11)	1.10 (0.04)	8.05 (0.45)	4.95 (0.16)
Goats (Kid)	2.60 (0.06)	-	4.00 (0.22)	2.30 (0.08)
Goats (Adult)	2.60 (0.06)	1.10 (0.04)	4.05 (0.23)	2.65 (0.09)
Sheep	22.10 (0.45)	28.75 (0.98)	24.50 (1.30)	25.12 (0.82)
Sheep (Lamb)	4.05 (0.09)	3.00 (0.10)	1.00 (0.06)	2.68 (0.09)
Sheep (Adult)	18.05 (0.36)	25.75 (0.88)	23.50 (1.24)	22.44 (0.74)
Others	2.30 (0.04)	1.05 (0.04)	2.00 (0.12)	1.58 (0.06)
Horse/Donkey/Mules	-	-	4.50 (0.25)	1.65 (0.06)
Adult Cattle Units	100 (2.10)	100 (3.30)	100 (5.50)	100 (3.30)

4.4.9. Income Structure

To assess the economic significance of different crops and *Pinus gerardiana* (neoza) in the livelihood of sampled households, the source-wise breakup of farm income across different farm categories was analyzed and is presented in Table 41. The data indicates that fruit crops were the primary source of income, contributing 71.80 per cent of the total household income at the overall level. Among different farm categories, the proportion of income from fruit crops was highest in small farms (78.60%) and medium farms (79.90%), while it was comparatively lower in marginal farms (50.20%). This confirms that apple cultivation was the dominant cash crop, generating the highest returns for the sampled households. Income from agriculture (field crops) contributed only 3.65 per cent at the overall level, with variations across farm sizes—marginal (3.80%), small (3.50%), and medium (3.70%)—indicating that staple crop cultivation played a relatively minor role in household earnings. Dairy farming also had a limited contribution, ranging between 1.23 per cent to 1.80 per cent across farm categories. The collection and sale of *Pinus gerardiana* (neoza) formed an additional income source, contributing 2.93 per cent to the total income at an overall level. It was most significant for marginal farmers (3.50%), indicating its importance as a supplementary livelihood activity, while small farmers had the lowest share (2.60%) from this source. Off-farm income, including employment and business, made up 20.40 per cent of total income at the overall level, but its share was highest among marginal farmers (40.70%) and lowest among medium farmers (12.76%), suggesting that smaller farmers relied more on non-farm employment due to lower earnings from agriculture.

Table 41: Farm category wise average income of sampled households in Kinnaur and Chamba district of Himachal Pradesh

Particulars	Marginal	Small	Medium	Overall
Farm				
Agriculture	40500 (3.80)	67000 (3.50)	98000 (3.70)	62000 (3.65)
Fruits	540000 (50.20)	1505000 (78.60)	2160000 (79.90)	1250000 (71.80)
Dairy	19500 (1.80)	23500 (1.23)	33500 (1.24)	24500 (1.40)
Sub Total	599000 (55.80)	1585500 (83.33)	2291500 (84.84)	1336500 (76.85)
<i>Pinus gerardiana</i>	37500 (3.50)	49500 (2.60)	81000 (3.00)	51000 (2.93)
Off-Farm	440000 (40.70)	277000 (14.07)	345000 (12.76)	355000 (20.40)
Total	1071500 (100)	1902000 (100)	2700000 (100)	1737500 (100)

4.5 Advances in molecular research

The genetic improvement of some forest trees is hindered by the narrow genetic base of available genotypes. Genotypes preserved in gene banks can contribute to the development of more profitable plant varieties; however, effectively utilizing such genetic material requires extensive

knowledge and understanding of the genetic variations present in both domesticated and wild genotypes. Various methods are available to identify genetic diversity among different genotypes, with molecular markers being among the most promising approaches.

This study employed ISSR markers to assess the genetic diversity of *Pinus gerardiana* populations in the dry temperate forests of Himachal Pradesh. These markers were chosen for their high polymorphism, reproducibility, and ability to detect genetic variation without requiring prior genomic information. The results revealed significant genetic differentiation among populations, suggesting that geographical and environmental factors play a crucial role in shaping genetic structure. The high level of polymorphism observed indicates a rich genetic reservoir, essential for the species' adaptability and long-term survival in changing environmental conditions. The effectiveness of ISSR markers in identifying distinct genetic clusters underscores their utility in assessing population structure and evolutionary relationships. These findings highlight the urgent need for conservation strategies aimed at preserving genetically diverse populations, as genetic variation is fundamental to resilience and adaptability. Additionally, the identification of unique genetic pools can facilitate the selection of superior genotypes for afforestation and ecological restoration programs. This study reinforces the significance of ISSR markers in understanding genetic resources, ultimately contributing to the sustainable management and conservation of *Pinus gerardiana* in its natural habitat. Gul *et al.* (2021) concluded that mid-altitude populations of *Pinus gerardiana* possess the highest genetic and phytochemical diversity, highlighting their value for conservation.

The ISSR marker-based analysis of *Pinus gerardiana* genotypes revealed substantial genetic polymorphism, demonstrating high genetic diversity within the species. All 15 primers successfully amplified DNA, producing distinct banding patterns across 25 genotypes, with 100 per cent polymorphism observed (Fig. 11). Among them, UBC-861 exhibited the highest Polymorphism Information Content (PIC) value (0.499), indicating its superior discriminatory power in differentiating genotypes, whereas UBC-809 had the lowest (0.035), suggesting lower informativeness. A higher PIC value reflects the genetic richness of a population, making such markers valuable for genetic diversity assessments (Motahari *et al.* 2021). Thus, conserving genetically diverse *Pinus gerardiana* genotypes is vital for sustainable utilization and ecological resilience (Kant *et al.* 2005). Strategic selection using ISSR markers ensures effective conservation and breeding outcomes.

Additionally, the Effective Multiplexing Ratio (EMR), which quantifies a primer's efficiency in amplifying multiple loci simultaneously, was highest for UBC-808, UBC-834, UBC-840, and n-ISSR-1 (6) and lowest for UBC-818, UBC-829, UBC-835, UBC-842, UBC-861 (3). A greater EMR suggests a primer's suitability for high-throughput genetic analysis, essential for studying complex genetic structures (Motahari *et al.* 2021). The Marker Index (MI), which measures the overall effectiveness of a marker system in distinguishing genetic variations, was highest for n-ISSR-2



Plate 7. Molecular analysis of *Pinus gerardiana* genotypes

(2.995) and lowest for UBC-809 (0.1466) (Table 42). MI integrates polymorphic information and marker efficiency, making it a crucial factor in evaluating marker utility for genetic differentiation (Li *et al.* 2024). Furthermore, the Resolving Power (RP), which assesses a primer's ability to distinguish genotypes based on banding patterns, was highest for n-ISSR-2 (5.76) and lowest for UBC-861 (1.52). Higher RP values suggest a primer's strong capability to detect genetic variations, a key criterion for selecting markers in genetic studies (Li *et al.* 2024). Moosavi *et al.* (2022) highlighted a moderate genetic variation in *Pinus gerardiana*, with stronger spatial genetic structure in young trees, urging conservation efforts to enhance natural regeneration.

These findings confirm the robustness of ISSR markers in assessing genetic diversity, emphasizing their applicability in conservation genetics and breeding programs for *Pinus gerardiana*. The variation in marker informativeness suggests that primers with high PIC and RP values, such as UBC-835 and UBC-825, are particularly useful for genetic differentiation and population structure analysis. Overall, this study provides valuable insights into the genetic composition of *Pinus gerardiana*, which can guide conservation strategies and the sustainable management of this species.

Table 42: Genetic diversity of chilgoza pine genotype using ISSR markers Kinnaur and Chamba district of Himachal Pradesh

Primer	No. of amplified alleles	No. of polymorphic allele	Polymorphism %	PIC	Rp	EMR	MI
UBC-807	4	4	100	0.357	1.92	4.0	1.427
UBC-808	6	6	100	0.475	2.44	6.0	2.848
UBC-809	2	2	100	0.035	2.00	4.2	0.147
UBC-811	6	5	100	0.245	2.00	4.2	1.022
UBC-818	3	3	100	0.484	2.48	3.0	1.452
UBC-823	4	4	100	0.349	2.88	4.0	1.395
UBC-825	5	5	100	0.324	2.16	5.0	1.619
UBC-829	3	3	100	0.467	2.24	3.0	1.402
UBC-834	6	6	100	0.467	5.04	6.0	2.803
UBC-835	3	3	100	0.478	2.40	3.0	1.434
UBC-840	6	6	100	0.432	4.32	6.0	2.592
UBC-842	4	4	100	0.485	2.32	4.0	1.495
UBC-861	3	3	100	0.348	1.52	3.0	1.043
n-ISSR-1	6	6	100	0.446	4.24	6.0	2.675
n-ISSR-2	6	6	100	0.499	5.76	5.0	2.995

4.5.1 Dendrogram

The dendrogram analysis of *Pinus gerardiana* genotypes based on ISSR marker data reveals significant genetic diversity among the sampled populations. The hierarchical clustering pattern

shows distinct genetic groupings, indicating variation in genetic composition among different genotypes. Genotypes such as Klp1, Klb1, Klp3, and Klp5 form a closely related cluster, suggesting high genetic similarity and potential common ancestry. Similarly, Poo1, Poo2, Poo3, Poo4, and Poo5 group together, reflecting their close genetic relationship. In contrast, genotypes such as Mrg5 and Klb5 branch out earlier in the dendrogram, signifying greater genetic divergence from the rest of the populations (Fig. 9, 10).

The variation in branch lengths along the coefficient scale highlights differences in genetic distances, with shorter branches within clusters indicating minimal genetic variation and longer branches suggesting substantial genetic differentiation. This clustering pattern suggests that geographical and environmental factors may have influenced the genetic structuring of these populations. The presence of genetically distinct clusters emphasizes the existence of diverse genetic pools, which is crucial for conservation and breeding strategies. From a conservation perspective, the high genetic diversity observed in the dendrogram underscores the importance of preserving genetically distinct populations to ensure the long-term adaptability and resilience of *Pinus gerardiana* in its natural habitat. Genotypes exhibiting close genetic relationships may be suitable candidates for selective breeding programs aimed at enhancing desirable traits. On the other hand, the identification of genetically distinct populations is valuable for conservation efforts, as maintaining genetic heterogeneity is essential for the species' sustainability. The results of this study provide a foundation for future afforestation and ecological restoration programs by enabling the selection of superior genotypes while preserving genetic diversity.

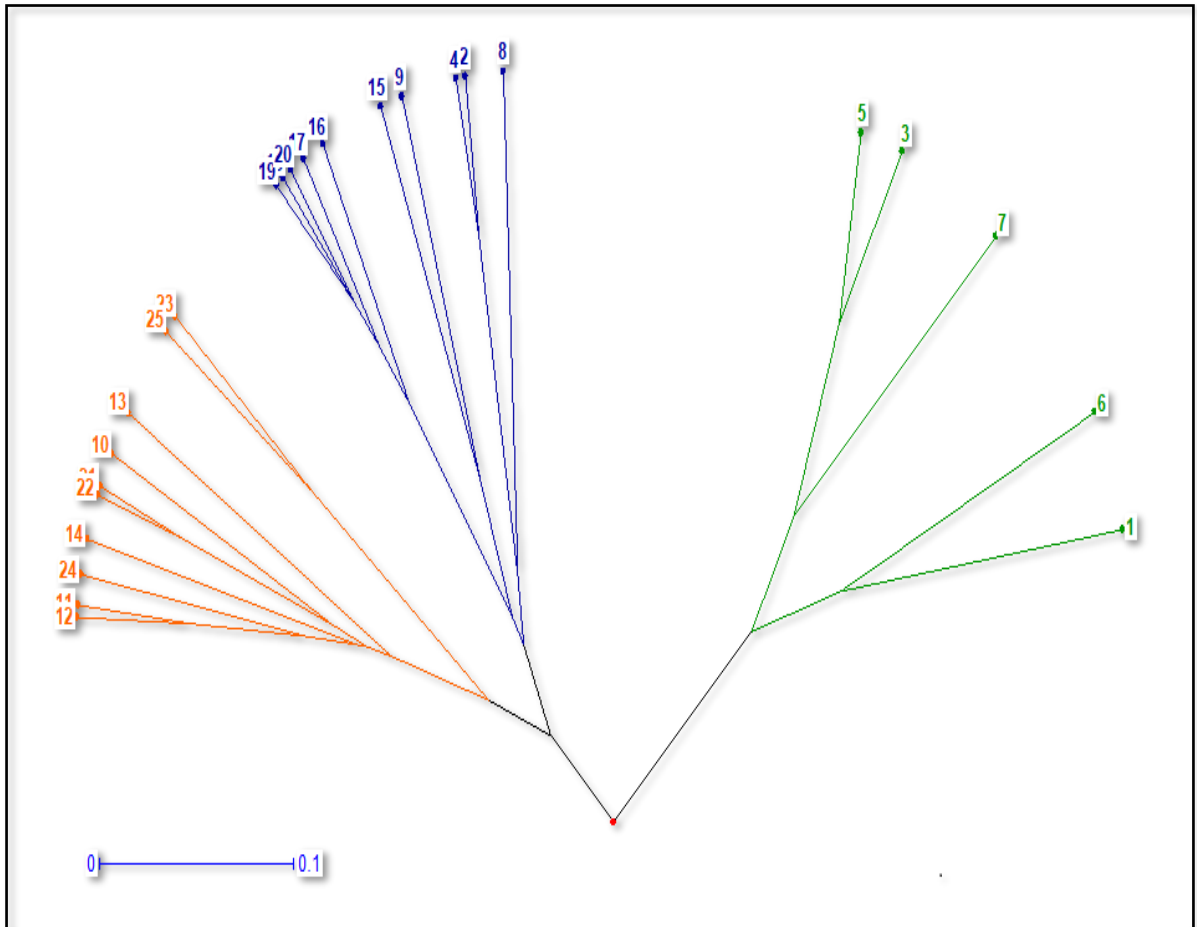
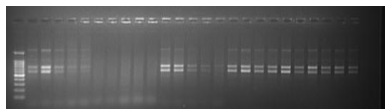
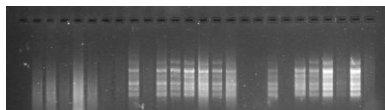


Fig. 10 Dendrogram growing from root based on Dice similarity coefficient. Software used: Darwin 6

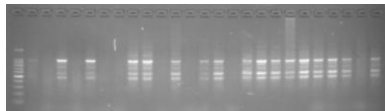
UBC-807



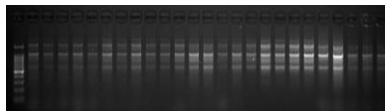
UBC-808



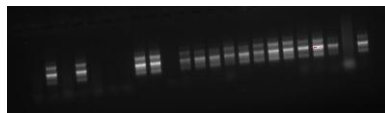
UBC- 809



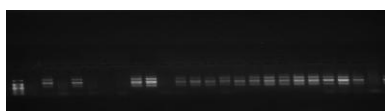
UBC-811



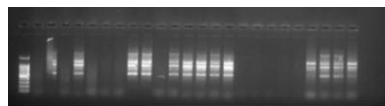
UBC- 818



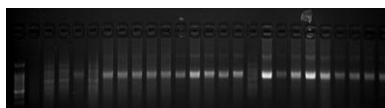
UBC-823



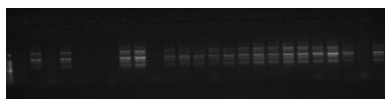
UBC- 825



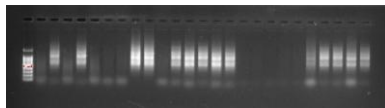
UBC-834



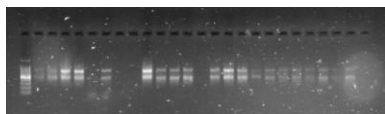
UBC-842



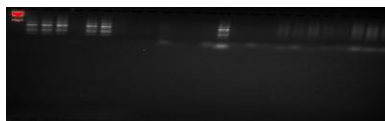
UBC-840



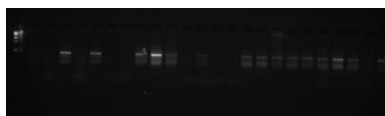
UBC-861



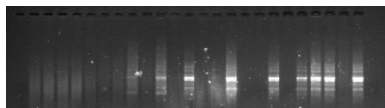
nISSR- 2



UBC-840



nISSR- 1



UBC-835

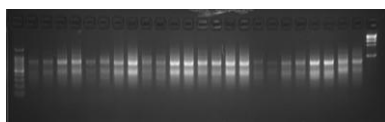


Fig. 11 ISSR based DNA banding patterns of *Pinus gerardiana* genotypes from different populations

Chapter - 5

SUMMARY AND CONCLUSIONS

The present study, titled “**Population Dynamics and Stand Structure of *Pinus gerardiana* Wall. in the Dry Temperate Forests of Himachal Pradesh,**” was conducted across four sites in Kinnaur and one in Chamba, Himachal Pradesh, India, during the years 2021–2025. The key findings of the investigation are summarized and concluded as follows:

5.1 Morphological traits and stand structure

The study examined tree growth traits across different sites. The tallest genotype (27.00 m) was found in Kilba, while the shortest (12.50 m) was in Pooh. The largest DBH (75.00 cm) was recorded in Moorang, and the smallest (38.50 cm) in Pooh. Crown width ranged from 7.50 m (Pangi) to 12.00 m (Kalpa and Pangi). The highest crown projection ratio (16.75) was observed in Kalpa, while the lowest (12.15) was in Pooh.

Solar influx varied, with the highest ($24.55 \mu\text{mol m}^{-2} \text{s}^{-1}$) in Kilba and the lowest ($20.55 \mu\text{mol m}^{-2} \text{s}^{-1}$) in Pooh, suggesting differences in light interception. Kilba had the highest mean height (21.40 m), while Pangi recorded the lowest (14.60 m). DBH was largest in Moorang (61.99 cm) and Pooh (60.46 cm), whereas Kalpa had the smallest (48.76 cm). The widest crowns were in Kilba (10.52 m) and Kalpa (10.16 m), while Moorang had the narrowest (9.26 m).

Genetic analysis showed that DBH had the highest phenotypic (33.11%) and genotypic (21.69%) variation, along with the highest genetic gain (29.27%) and genetic advance (16.58), making it a key trait for selection. Solar influx had the highest heritability (89.51%), indicating strong genetic control with minimal environmental influence.

A correlation study revealed significant relationships among growth parameters. DBH correlated with height (0.56) at the 5 per cent significance level, while crown projection ratio correlated with crown width (0.59) at the 1 per cent level.

Principal component analysis identified three key components. Component I (39.10% variance) had the highest loading for height (0.91), followed by DBH (0.80). Component II (26.2% variance) was dominated by solar influx (0.68) and DBH (0.57). Component III (20.2% variance) was mainly influenced by crown projection ratio (0.43). The 25 genotypes were grouped into three clusters. Cluster II had the most genotypes (11), Cluster I contained 8, and Cluster III had the least (6).

Significant variation was observed in needle, cone, and seed traits. Needle length ranged from 7 cm (T24) to 9.2 cm (T17). Cone length varied from 10.2 cm (T18) to 16.6 cm (T6), while cone

width ranged from 8.2 cm (T7) to 10.7 cm (T11). The longest seed (23.4 mm) was found in T12, and the shortest (17 mm) in T21. Seed width varied from 5.2 mm (T1) to 7.3 mm (T20). The highest 100-seed weight (59 g) was recorded in T20 and T7, while the lowest (40 g) was in T25.

Site-wise, the longest needle length was in Pooh (8.56 cm), and the shortest cone width was in Kalpa (8.91 cm). Moorang had the largest DBH (61.99 cm) and narrowest crowns (9.26 m), while Kalpa had the smallest DBH (48.76 cm) but the highest crown projection ratio (16.41). The highest solar influx ($24.09 \mu\text{mol m}^{-2} \text{s}^{-1}$) was in Kalpa, while the lowest ($21.08 \mu\text{mol m}^{-2} \text{s}^{-1}$) was in Pooh. Genetic analysis showed needle length had the highest phenotypic (15.70%) and genotypic (15.04%) variation, along with the highest genetic gain (29.69%) and heritability (92.23%), making it a key trait for selection. In contrast, 100-seed weight had the highest genetic advance (8.19%), suggesting strong genetic control.

Correlation analysis found significant relationships: cone width with needle length (0.46), seed length with needle length (0.55), and seed width with both needle length (0.46) and seed length (0.66). The 100-seed weight strongly correlated with seed length (0.72). Principal component analysis revealed that Component I (45.50% variance) was dominated by needle length (0.988) and 100-seed weight (0.84), while Component II (21.60% variance) had the highest loading for 100-seed weight (0.48).

The 25 genotypes were grouped into three clusters. Cluster III had the most genotypes (14), Cluster II had 6, and Cluster I had the fewest (5). Kilba had the highest total tree percentage (64.33%), indicating strong regeneration and a favourable growing environment, followed by Pangl (42.50%) and Moorang (35.37%), which showed balanced distributions. Pooh (30.86%) had more trees in mid-sized classes (30–50 cm), while Kalpa had the lowest (30.24%), suggesting slower growth or regeneration challenges. Kilba peaked in the 30–50 cm range, while Pangl and Moorang had well-distributed mature and regenerating trees. Pooh showed better recruitment in smaller classes, whereas Kalpa lacked larger trees, indicating possible regeneration issues.

5.2 Phytosociological insights

In this Kalpa range, *Pinus gerardiana* was the most dominant tree species (IVI: 212.85), followed by *Cedrus deodara* and *Pinus wallichiana*. Among shrubs, *Indigofera cedororum* had the highest IVI (51.78), while *Daphne oleoides* had the lowest (14.07). In the herbaceous layer, *Artemisia capillaris* was the most dominant (IVI: 55.09), whereas *Ranunculus hirtellus* had the lowest IVI (8.67), indicating its limited presence.

In the Kilba Range, *Pinus gerardiana* was the most dominant tree species (IVI: 161.19), followed by *Quercus ilex* and *Cedrus deodara*, while *Olea cuspidata* had the lowest IVI (20.83).

Among shrubs, *Rhus cotinus* exhibited the highest IVI (39.79), whereas *Lonicera hypoleuca* had the lowest (16.78). In the herbaceous layer, *Artemisia maritima* was the most dominant (IVI: 57.13), while *Morina longifolia* had the lowest IVI (9.79), indicating its minimal presence.

In the Moorang range, *Pinus gerardiana* was the most dominant tree species (IVI: 177.85), followed by *Cedrus deodara* and *Fraxinus micrantha*, while *Pinus wallichiana* had the lowest IVI (11.66). Among shrubs, *Rhus cotinus* exhibited the highest IVI (55.28), whereas *Rosa webbiana* had the lowest (24.19). In the herbaceous layer, *Artemisia capillaris* was the most dominant (IVI: 49.24), while *Rumex nepalensis* had the lowest IVI (6.48), indicating its minimal presence.

In Pooh range, *Pinus gerardiana* was the most dominant tree (IVI: 194.53), followed by *Cedrus deodara* and *Fraxinus micrantha*. Among shrubs, *Juniperus communis* had the highest IVI (162.50), while *Ephedra gerardiana* had the lowest (52.34). In the herbaceous layer, *Artemisia maritima* was the most dominant (IVI: 66.11), whereas *Myosotis sylvatica* had the lowest (11.69), indicating its minimal presence.

In this Pangl range, *Pinus gerardiana* was the most dominant tree species (IVI: 127.90), followed by *Cedrus deodara* and *Pinus wallichiana*, while *Juglans regia* had the lowest IVI (7.18). Among shrubs, *Berberis aristata* showed the highest dominance (IVI: 68.46), whereas *Aster albescens* had the lowest (11.00). In the herbaceous layer, *Artemisia nilagarica* was the most dominant (IVI: 67.32), while *Thalictrum foliolosum* had the lowest (35.41), indicating its limited presence.

Tree diversity was highest in Pangl ($H = 1.18$), followed by Kilba ($H = 1.02$), while Kalpa had the lowest ($H = 0.41$). The Simpson dominance index (D) was highest in Kalpa (0.81), indicating strong species dominance, whereas Pangl had the highest Simpson diversity index ($1-D$) (0.56) and species richness ($Dmg = 1.30$).

Among shrubs, diversity was highest in Kilba ($H = 2.32$) and lowest in Pooh ($H = 1.06$). Pooh also had the highest dominance ($D = 0.36$), while Kilba had the lowest ($D = 0.11$) and the highest Simpson diversity index ($1-D = 0.89$), showing an even species distribution.

For herbs and grasses, Moorang ($H = 2.75$) and Kalpa ($H = 2.76$) exhibited the highest diversity, while Pangl ($H = 1.76$) had the lowest. Kalpa and Moorang had the lowest dominance ($D = 0.07$) and highest species heterogeneity ($1-D = 0.93$).

Tree species similarity was highest between Kalpa-Kilba (1.00) and lowest between Kalpa-Pooh (0.73). For shrubs, Kalpa-Pangl (0.89) showed high similarity, while Kilba-Pooh (0.34) was the lowest. Among herbs, Kalpa-Moorang (0.97) had the highest similarity, while Kalpa-Pangl (0.60) was the lowest.

5.3 Natural regeneration and soil nutrient interactions

In Kalpa, *Pinus gerardiana* had the highest recruits (500 ha^{-1}) and the best regeneration success (25.83%). *Cedrus deodara* (18.75%) and *Pinus wallichiana* (15%) showed lower regeneration success.

In Kilba, *Pinus gerardiana* had the highest recruits (666.67 ha^{-1}) and regeneration success (22.50%). *Cedrus deodara* showed better survival (establishment stocking: 15%, regeneration success: 16.25%), while *Quercus ilex* had the lowest regeneration success (13.33%).

In Moorang, *Pinus gerardiana* had the highest recruits (1166.67 ha^{-1}) and regeneration success (44.17%), showing strong survival. *Cedrus deodara* had lower establishment stocking (11.69%) but relatively high regeneration success (40%).

In Pooh, *Pinus gerardiana* had the highest recruits (833.33 ha^{-1}) with better regeneration success (23.33%) and establishment stocking (15.38%). *Cedrus deodara* had lower values (9.88% stocking, 12.50% regeneration).

In Pangi, *Pinus gerardiana* had the highest recruits (916.67 ha^{-1}) with the best regeneration success (33.33%) and establishment stocking (23.94%). *Cedrus deodara* followed (32.50% regeneration, 10.57% stocking), while *Celtis australis* had the lowest values (6.25% regeneration, 4.53% stocking).

Kilba had the highest nitrogen ($204.40 \text{ kg ha}^{-1}$) and Pooh the lowest ($171.90 \text{ kg ha}^{-1}$), with values decreasing by depth. Phosphorus peaked in Kalpa (22.70 kg ha^{-1}) and was lowest in Pooh (19.50 kg ha^{-1}). Potassium was highest in Kalpa ($483.50 \text{ kg ha}^{-1}$) and lowest in Pooh ($413.40 \text{ kg ha}^{-1}$), also declining with depth. Organic carbon was highest in Pooh (1.16%) and lowest in Kalpa and Pangi (1.12%), with surface layers retaining more carbon.

Soil pH ranged from 6.23 to 6.68, highest in Pooh (6.51) and lowest in Kalpa (6.41), increasing with depth. Bulk density rose with depth, highest in Pangi (1.37 g cm^{-3}) and lowest in Kilba (1.33 g cm^{-3}). Electrical conductivity (EC) declined with depth, peaking in Pangi (0.20 dS m^{-1}) and lowest in Kalpa (0.17 dS m^{-1}). Soil moisture was highest in Kalpa (31.97%) and lowest in Pooh (28.74%), decreasing with depth.

5.4 Socio-Economic status

The region was dominated by joint families, comprising 65 per cent of households overall. The proportion of joint families ranged from 54.55 per cent in marginal households to 72.00 per cent in medium-sized households. The average family size was 6.15 members, with males (42.00%), females (38.54%), and children (19.46%).

On average, family size ranged from 5 members in marginal households to 8 in medium households, with an overall average of 6 members. Males constituted 41.59 per cent, females 38.01 per cent, and children 20.40 per cent (11.37% male and 9.03% female).

The overall literacy rate was 83.8 per cent, ranging from 78.1 per cent to 89 per cent across farm categories. Male literacy (89.2%) was higher than female literacy (78.8%). The literacy index stood at 2.95, varying from 2.7 in marginal households to 3.35 in small farms, indicating disparities in education quality. Intermediate-level education was most common (25.92%), while postgraduate attainment remained low (4%).

Occupational distribution revealed that 77.75 per cent of the workforce engaged in farming. Additionally, 5.50 per cent combined agriculture with business, while 6.70 per cent pursued both agriculture and services. Public sector jobs employed 4.79 per cent, private sector 3.35 per cent, and 1.91 per cent were self-employed in business.

At the overall level, 65.11 per cent of family members were workers. The highest worker percentage was in marginal farms (66.91%) and the lowest in small farms (63.93%). The overall dependency ratio was 0.54 concerning total workers and 0.35 concerning family size, indicating that, on average, one worker supports less than one dependent.

At the overall level, male farm workers (50.80%) slightly outnumbered female workers (49.20%). However, in the small farm category, female workers were more prevalent than male workers.

The average landholding of sampled households was 1.43 hectares, with 68.53 per cent as operational holding, including 50.35 per cent under fruit trees and 18.18 per cent under crops. Of the total cultivated land, 67.13 per cent was irrigated. Additionally, 15.38 per cent of land was under forests, 4.90 per cent was uncultivated/waste land, and 4.20 per cent was used for non-agricultural purposes.

At the overall level, 58.60 per cent of the gross cropped area was under fruit crops. Rajma was the predominant Kharif crop, while barley dominated in the Rabi season. The overall cropping intensity was 124.49 per cent. The livestock inventory showed that each household had an average of 3.23 ACUs, with cattle accounting for 67.49 per cent, sheep 24.77 per cent, and goats 4.64 per cent. The income structure showed that fruit crops contributed 71.80 per cent of total household income, with the highest share in medium (79.90%) and small farms (78.60%), while it was lower in marginal farms (50.20%). Agriculture contributed only 3.65 per cent, while dairy farming ranged between 1.23 per cent and 1.80 per cent. *Pinus gerardiana* (neoza) contributed 2.93 per cent, being most significant

for marginal farmers (3.50%). Off-farm income made up 20.40 per cent, with the highest share in marginal farms (40.70%) and the lowest in medium farms (12.76%).

5.5 Genetic diversity study of chilgoza pine

The ISSR marker-based analysis of *Pinus gerardiana* genotypes revealed significant genetic diversity, with all 15 primers successfully amplifying DNA and achieving 100 per cent polymorphism. UBC-861 showed the highest Polymorphism Information Content (PIC) value (0.499), indicating strong discriminatory power, while UBC-809 had the lowest (0.035). Effective Multiplexing Ratio (EMR) was highest for UBC-808, UBC-834, UBC-840, and n-ISSR-1 (6), highlighting their efficiency in amplifying multiple loci.

Marker Index (MI) was highest for n-ISSR-2 (2.995), and Resolving Power (RP) was highest for n-ISSR-2 (5.76), signifying strong genotype differentiation potential. These results confirm the effectiveness of ISSR markers in genetic diversity assessment, with high-PIC and high-RP primers like UBC-835 and UBC-825 being particularly useful for genetic studies and conservation efforts.

The dendrogram analysis of *Pinus gerardiana* genotypes based on ISSR markers highlights significant genetic diversity and distinct clustering patterns. Closely related genotypes, such as Klp1, Klb1, Klp3, and Klp5, form tight clusters, while others like Mrg5 and Klb5 show greater genetic divergence. Variations in branch lengths indicate differing genetic distances, likely influenced by geographical and environmental factors. This genetic structuring is crucial for conservation and breeding, as maintaining diverse genetic pools ensures adaptability and resilience. The findings provide a basis for afforestation and restoration efforts, enabling the selection of superior genotypes while preserving genetic diversity.

Conclusions

- ✓ The study revealed significant genetic and phenotypic variations in growth, needle, cone, and seed traits among different chilgoza pine genotypes. DBH and needle length emerged as key selection traits due to their high heritability and genetic gain.
- ✓ Site-wise variations indicated Kilba as the most favourable site for growth and regeneration, while Kalpa showed possible regeneration challenges. Overall, the findings highlight the importance of genetic selection for improving chilgoza pine conservation and productivity.
- ✓ *Pinus gerardiana* was the dominant tree species across all ranges, with the highest IVI in Kalpa (212.85) and the lowest in Pangi (127.90). Among shrubs, *Juniperus communis* (Pooh) and *Berberis aristata* (Pangi) exhibited the highest IVI, while *Indigofera cedororum* (Kalpa)

and *Aster albescent* (Pangi) had the lowest. In the herbaceous layer, *Artemisia* species were the most dominant across sites.

- ✓ Tree diversity was highest in Pangi ($H = 1.18$) and lowest in Kalpa ($H = 0.41$), while shrub diversity peaked in Kilba ($H = 2.32$). Herbaceous diversity was highest in Kalpa and Moorang ($H = 2.76$). Species similarity was greatest between Kalpa-Kilba for trees and Kalpa-Moorang for herbs, while the lowest similarity was observed between Kilba-Pooh for shrubs.
- ✓ *Pinus gerardiana* had the highest recruits and regeneration success across all sites, with the best survival in Moorang (44.17%) and Pangi (33.33%).
- ✓ *Cedrus deodara* showed moderate regeneration, while *Quercus ilex* and *Celtis australis* had the lowest success rates. Kilba recorded the highest nitrogen ($204.40 \text{ kg ha}^{-1}$), while Pooh had the lowest ($171.90 \text{ kg ha}^{-1}$). Phosphorus and potassium peaked in Kalpa but declined with depth. Organic carbon was highest in Pooh (1.16%) and lowest in Kalpa and Pangi (1.12%), with surface layers retaining more carbon.
- ✓ Soil pH ranged from 6.23 to 6.68, highest in Pooh (6.51), while bulk density and electrical conductivity were highest in Pangi. Soil moisture was highest in Kalpa (31.97%) and lowest in Pooh (28.74%), decreasing with depth. The region had a predominance of joint families (65%), with an average family size of 6.15 members.
- ✓ Literacy stood at 83.8 per cent, higher among males (89.2%) than females (78.8%), with intermediate education being the most common. Farming was the primary occupation (77.75%), while 6.70 per cent engaged in both agriculture and services.
- ✓ The dependency ratio was 0.54, and female workers outnumbered males in small farms. The average landholding was 1.43 ha, with 68.53 per cent operational, 50.35 per cent under fruit trees, and 67.13 per cent irrigated. Fruit crops contributed 71.80 per cent of household income, while off-farm income was highest in marginal farms (40.70%).
- ✓ ISSR marker analysis of *Pinus gerardiana* revealed high genetic diversity, with all 15 primers showing 100 per cent polymorphism. UBC-861 had the highest PIC (0.499), while UBC-809 had the lowest (0.035). n-ISSR-2 exhibited the highest Marker Index (2.995) and Resolving Power (5.76), indicating strong genotype differentiation.
- ✓ Dendrogram analysis showed distinct clustering, with closely related genotypes forming tight clusters and others displaying genetic divergence. These findings support conservation and breeding efforts by identifying diverse and resilient genotypes for afforestation and restoration.

Recommendations

Based on the study, DBH and needle length are key traits for selection due to their high genetic gain and heritability. Kilba and Moorang emerge as ideal sites for growth traits, while Pooh excels in needle characteristics. Genotypes like T17, T20, and T12 are recommended for reproductive traits. Cluster-based breeding combining growth and seed traits is suggested for balanced improvement.

Based on the vegetation analysis, Pangi and Kilba should be prioritized for conservation and biodiversity enhancement due to their high tree and shrub diversity. Kalpa, with its strong dominance and low diversity, needs species enrichment and reforestation efforts to balance ecological structure. Moorang and Kalpa show excellent herbaceous diversity, making them ideal for herbal resource conservation and study sites. Cross-site conservation planning should focus on Kalpa-Kilba and Kalpa-Moorang due to their high species similarity, ensuring effective regional biodiversity management.

Based on regeneration and soil characteristics, Moorang and Pangi are best suited for conservation and natural regeneration efforts, showing high *Pinus gerardiana* recruitment and regeneration success. Kalpa, despite strong regeneration of *Cedrus deodara*, needs improved soil organic carbon and pH balancing to enhance overall soil health. Pooh shows poor regeneration and lowest nutrient levels; it requires soil enrichment (NPK) and organic amendments for ecological restoration. Kilba, with high nitrogen and moderate regeneration, is ideal for silvicultural management and mixed-species plantations to optimize both growth and biodiversity.

With *Pinus gerardiana* contributing significantly to marginal farmers' income and showing strong regeneration in several ranges, it should be prioritized for sustainable harvesting, value addition, and conservation. Promoting community-based management and providing training in seed collection and processing can enhance income. Integrating neoza into agroforestry models and securing market linkages will further boost its economic value while ensuring ecological sustainability.

To conserve and sustainably utilize *Pinus gerardiana*, it is crucial to prioritize genotypes with high genetic diversity and distinct traits, as revealed by ISSR marker analysis. High-PIC and high-RP primers like UBC-835 and n-ISSR-2 should be used for ongoing diversity monitoring and selection programs. Genotypes showing strong genetic divergence should be preserved in situ and ex situ to maintain adaptability. Additionally, breeding and afforestation efforts should focus on genetically diverse and resilient genotypes to enhance forest regeneration and ecological stability.

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APPENDIX

Appendix I: Analysis of Variance table for different growth traits of *Pinus gerardiana* genotypes

Tree diameter					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	810.114			
Treatment	4	764.766	191.191	0.952	0.46
Error	16	3,214.16	200.885		
Total	24	4,789.04			
Tree height					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	15.64			
Treatment	4	152.44	38.11	3.473	0.032
Error	16	175.56	10.973		
Total	24	343.64			
Crown width					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	4.372			
Treatment	4	4.368	1.092	0.426	0.788
Error	16	41.042	2.565		
Total	24	49.782			
Crown projection ratio					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	0.697			
Treatment	4	13.996	3.499	5.729	0.005
Error	16	9.772	0.611		
Total	24	24.466			
Solar influx					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	2.754			
Treatment	4	31.815	7.954	25.637	< 0.001
Error	16	4.964	0.31		
Total	24	39.533			

Appendix II: Analysis of Variance table for different needle, cone and seed characteristics among *Pinus gerardiana* genotypes

Needle length					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	0.642			
Treatment	4	5.618	1.405	11.46	< 0.001
Error	16	1.961	0.123		
Total	24	8.221			
Cone length					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	8.698			
Treatment	4	4.866	1.217	0.357	0.835
Error	16	54.47	3.404		
Total	24	68.034			
Cone width					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	1.498			
Treatment	4	0.962	0.241	1.369	0.289
Error	16	2.811	0.176		
Total	24	5.271			
Seed length					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	2.865			
Treatment	4	82.593	20.648	47.668	< 0.001
Error	16	6.931	0.433		
Total	24	92.389			
Seed width					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	0.816			
Treatment	4	3.808	0.952	20.355	< 0.001
Error	16	0.748	0.047		
Total	24	5.373			
100 Seed weight					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	4	45.89			
Treatment	4	505.786	126.447	11.821	< 0.001
Error	16	171.153	10.697		
Total	24	722.83			

Appendix III: Analysis of Soil macronutrients status and Soil physicochemical properties different range of chilgoza pine forest in Himachal Pradesh

pH					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	0.051			
Families (A)	4	0.057	0.014	4.664	0.005
Genotype (B)	2	0.661	0.33	108.711	< 0.001
Intraction A X B	8	0.029	0.004	1.209	0.33
Error	28	0.085	0.003		
Total	44	0.883			
Bulk Density					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	0.008			
Families (A)	4	0.007	0.002	1.02	0.414
Genotype (B)	2	0.221	0.111	60.697	< 0.001
Intraction A X B	8	0.003	0	0.193	0.99
Error	28	0.051	0.002		
Total	44	0.29			
Electrical Conductivity					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	0.002			
Families (A)	4	0.004	0.001	17.013	< 0.001
Genotype (B)	2	0.031	0.015	273.147	< 0.001
Intraction A X B	8	0	0	0.726	0.668
Error	28	0.002	0		
Total	44	0.038			
Soil Moisture Content					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	1.232			
Families (A)	4	77.423	19.356	9.959	< 0.001
Genotype (B)	2	113.864	56.932	29.293	< 0.001
Intraction A X B	8	3.918	0.49	0.252	0.976
Error	28	54.419	1.944		
Total	44	250.856			
Available N (kg ha⁻¹)					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	3,462.44			
Families (A)	4	5,334.13	1,333.53	2.175	0.098
Genotype (B)	2	63,964	31,982.1	52.157	< 0.001
Intraction A X B	8	498.137	62.267	0.102	0.999
Error	28	17,169.35	613.191		
Total	44	90,428.3			

Available P (kg ha⁻¹)					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	19.265			
Families (A)	4	46.521	11.63	6.715	0.001
Genotype (B)	2	445.25	222.625	128.535	< 0.001
Intrraction A X B	8	4.969	0.621	0.359	0.934
Error	28	48.497	1.732		
Total	44	564.502			
Available K (kg ha⁻¹)					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	10,003.81			
Families (A)	4	32,501	8,125.34	8.696	< 0.001
Genotype (B)	2	1,80,929	90,464	96.818	< 0.001
Intrraction A X B	8	8,049.72	1,006.22	1.077	0.407
Error	28	26,162.45	934.373		
Total	44	2,57,646			
Organic Carbon (%)					
Source of Variation	DF	Sum of Squares	Mean Square	F-Calculated	Significance
Replication	2	0.004			
Families (A)	3	0.014	0.005	0.264	0.85
Genotype (B)	2	1.407	0.703	39.644	< 0.001
Intrraction A X B	6	0.028	0.005	0.262	0.949
Error	22	0.39	0.018		
Total	35	1.843			

General information

i) Name of the Respondent:

ii) Age:

iii) Sex:

iv) Economic status: APL / BPL

v) Beat:

vi) Block:

vii) Range:

viii) District: Kinnaur

ix) Family type: Joint / Nuclear

x) No of family members: Male Female Children

Sr.no.	Relationship with head	Age	Education I/P/M/H/D/S/NS	Occupation	
				Particulars	Income (Rs.)
1					
2					
3					
4					
5					
6					

I-Illiterate, P- Primary, M- Middle, H-High /Sr.Secondary, D- Degree and above,
S- School going, NS- Non school going

2. Land utilization pattern (bigha or ha)

Sr.no	Particulars of land	Area
1	Total land holding(owned)	
2	Total area under Chilgoza	
3	Pastures land / Barren land	
4	Land put to non-agricultural use	
5	Proportionate use of land for agriculture (%)	
6	Others	
7	Total holding	

a. Inventory of buildings

Sr.no	Particulars	Kucha		Pukka	
		No. & Year of construction	Cost(Rs.)	No. & Year of construction	Cost(Rs.)
1	Residential house				
2	Cattle shed				
3	Store house				
4	Other (specify)				

b. Source of irrigation

Source	Natural spring	Kuhl	Lift irrigation	Tanks	Rain water harvesting	Tubewell	Other specify
Private owned							
Govt. owned							
Community owned							
Adequacy of source							

c. Inventory of irrigation structures

Sr.no	Source of irrigation	Type of construction	Year of construction	Cost of construction
1	Kuhl			
2	Tank			
3	Pipe line			
4	Drip irrigation			
5	Sprinkles			
6	Any other			

d. Cropping pattern and production details (Bigha)

Crop	Area Production (bigha) (qtl.)		Home consumed	Marketed	
				Qty	value
Kharif crops					
Rabi					

[illegible]

e. Livestock inventory

Sr.no	Particulars	Number			Milk yield/ day(lts)	Year of purchase	Present value(Rs.)
		No	Crossbred	Local			
1	Cow i)Milch ii)Dry						
2	Buffalo i)Milchii)Dry						
3	Goat						
4	Ox						
5	Poultry						
6	Others						

f. Record of animal products & utilization

Type of product	Use		
	Home consumed quantity	Sold	
		Qty	Value
Milk			
Meat / Chicken			
Milk Products			
Eggs			
Manure			
Others			

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Title of Thesis : **Population Dynamics and Stand Structure of *Pinus gerardiana* Wall. in Dry Temperate Forests of Himachal Pradesh**
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ABSTRACT

The present study, titled "Population Dynamics and Stand Structure of *Pinus gerardiana* Wall. in Dry Temperate Forests of Himachal Pradesh," was conducted during 2021 to 2025 across five Chilgoza pine forest ranges: Kalpa, Kilba, Moorang, and Pooh in Kinnaur district, and Pangri in Chamba. These sites encompass the species' entire distribution range. The research aimed to evaluate various growth traits, including height, diameter at breast height (DBH), crown width, crown projection ratio, solar influx, needle length, cone length, cone width, seed length, seed width, and 100-seed weight among different genotypes. The study revealed significant variability across all traits, with mean values recorded as follows: height (18.40 m), DBH (56.70 cm), crown width (9.90 m), crown projection ratio (15.50 m), solar influx (22.70), needle length (7.8 cm), cone length (13.6 mm), cone width (9.2 cm), seed length (20.5 mm), seed width (6.2 mm), and 100-seed weight (51.5 g). Variability estimates, genetic parameters, correlation studies, principal component analysis, and divergence analysis confirmed high genetic variability among genotypes. Traits with high heritability included solar influx ($h^2 = 89.51$), crown projection ratio ($h^2 = 61.73$), DBH ($h^2 = 42.91$), needle length ($h^2 = 92.23$), and seed length ($h^2 = 90.23$), all of which exhibited substantial genetic gain. Phytosociological assessments confirmed *Pinus gerardiana* as the dominant tree species, with the highest IVI value in Kalpa (212.85) and the lowest in Pangri (127.90). Regeneration success was highest in Moorang (44.17%) and lowest in Kalpa (25.83%). Soil analysis indicated that Kilba had the highest nitrogen content (204.40 kg ha⁻¹), while Kalpa exhibited the highest phosphorus (22.70 kg ha⁻¹) and potassium (483.50 kg ha⁻¹) concentrations. Socioeconomic findings revealed a predominance of joint families (65%), a literacy rate of 83.8%, and farming as the primary occupation (77.75%). *Pinus gerardiana* contributed 3.71 per cent to farm income, with marginal farmers benefiting the most (5.90%), underscoring its economic significance for smaller landholders. Genetic diversity analysis using ISSR markers confirmed high polymorphism (100%), with UBC-861 exhibiting the highest polymorphic information content (0.499). Cluster analysis identified distinct genetic groupings, highlighting variation influenced by geographical and environmental factors. The findings underscore the ecological and economic importance of *Pinus gerardiana* and provide critical insights for its conservation and sustainable management.

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