VERTICAL VARIATION IN PHYSICO-CHEMICAL AND MECHANICAL PROPERTIES OF *Melia dubia* Cav.

Thesis

by

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(F-2019-83-M)

submitted to

Dr. YASHWANT SINGH PARMAR UNIVERSITY OF HORTICULTURE AND FORESTRY SOLAN (NAUNI) HP-173 230 INDIA

in

partial fulfilment of the requirements for the degree

of

MASTER OF SCIENCE (FORESTRY)

WOOD SCIENCE AND TECHNOLOGY
DEPARTMENT OF FOREST PRODUCTS
COLLEGE OF FORESTRY

2021

FRONTISPIECE

***Melia dubia* Cav.**

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CERTIFICATE - I

This is to certify that the thesis titled **"Vertical variation in physico-chemical and mechanical properties of *Melia dubia* Cav."** submitted in partial fulfillment of the requirements for the award of the degree of **Master of Science** (**Forestry)** in the discipline of **Wood Science and Technology** of Dr Yashwant Singh Parmar University of Horticulture and Forestry, (Nauni) Solan (HP)-173230 is a bonafide research work carried out by **Ms. Vaishali Modgill (F-2019-83-M)** daughter of Shri. Ram Sawroop Dhiman under my supervision and no part of this thesis has been submitted for any other degree or diploma.

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

Place: Nauni, Solan
Dated: __/__/2021

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ACKNOWLEDGEMENTS

First and foremost, I want to thank the almighty God for giving me strength and ability to understand learn and complete this task. After god, I owe this pride place to my beloved parents **Shri. Ram Sawroop Dhiman**, **Smt. Sushma Dhiman** and brother **Akhil Modgill** for their heartfelt blessings.

I consider myself fortunate to have the opportunity to pursue research work toward the M. Sc. under the supervision of **Dr. Rajneesh Kumar**. This thesis would not have been possible without his help, support and patience. His advice and unsurpassed knowledge of the subject helped me to achieve the title. I am extremely grateful for his suggestions and support on both academic and personal level.

I express my sincere thanks to the worthy members of my advisory committee **Dr. Meenu Sood** (Professor and Head), **Dr. Bhupender Dutt** (Professor), **Dr. Dushyant Sharma** (Assistant Professor) and **Dr. Rohit Sharma** (Assistant Professor) for their valuable suggestions, timely help and brilliant discussion during my studies.

I cordially acknowledge the help and assistance extended by the faculty, office, and lab and field staff of the Department of Forest Products **Mrs. Chitra Bhardwaj mam, Mr. Nand Lal Sharma, Mr. Mohan Lal** and **Mr. Bant Ram** for cooperation in lab for partial fulfillment of my research work.

I wish to record my deep gratitude to friends **Vaishali Sharma, Divya, Komal Thakur, Ankita Bhatia, karina, shalaka, Aman Zintoo** and **Vidyut Sharma** and my labmates **Tarun, Parsa, Tanya** and **Tamanna**. My special thanks to my juniors **Arshiya Prashar, Deeksha Kalsi, Shreya Patyal, Ruchi** and **Pooja** for their help and support.

It will be unfair if I will not say my special thanks to my senior cum friends **Mohit Shukla Sir, Sunny Sir, Dr. Heena Mam, Akshay Pingle Sir, Tapan Sir, Saurabh Sir, Jayashree Mam** and **Shivani Mam** for very moment spent with them, it will be a life time memory.

I am also thankful to the non-teaching staff of **College of Forestry** and **Satyanand Stokes** Library Dr. Yashwant Singh Parmar, University of Horticulture and Forestry, Nauni, Solan, for furnishing my studies with endless and invaluable information. I wish to thanks all those whom I might have missed out.

Needless to say Errors and Omissions are mine.

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LIST OF ABBREVIATIONS

%	:	Per cent
CD	:	Critical Difference
g	:	Gram
HP	:	Himachal Pradesh
kN	:	Kilo Newton
Mm	:	Millimeter
^{o}C	:	Degree Centigrade
pp.	:	Pages
CRD	:	Completely Randomized Design
SE	:	Standard Error
µm	:	Micrometer
DBH	:	Diameter at Breast Height
i.e.	:	that is
viz	:	videlicet (namely)
etc.	:	et cetera (and other similar things)
MPa	:	Mega Pascal
ANOVA	:	Analysis of Variance
MC	:	Moisture Content
TAPPI	:	Technical Association of Pulp and Paper Industry
N/mm^3	:	Newton per Cubic Millimeter
Kg/cm^3	:	Kilogram per Cubic Centimeter
MOE	:	Modulus of Elasticity
MOR	:	Modulus of Rupture
MMC	:	Maximum Moisture Content
GS	:	Average Density of wood substance
cm^3	:	Cubic Centimeter
sp. or spp.	:	Species
et al.	:	And others
pH	:	Potential of Hydrogen
m	:	Meter
cm	:	Centimeter
R^2	:	Coefficient of Determination
SG	:	Specific Gravity
g/cm^3	:	Gram per Centimeter Cube

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Chapter-1

INTRODUCTION

Forests are an integral part of mankind which provides wide range of end uses ranging from fuel wood to large timbers. Tree and their derivative products have been used by societies for thousands of years around the world. They are the only source of raw material for many wood based industries which are shrinking under acute socio-economic pressure. In India, forests were being denuded at an alarming rate but have been fortunately come down with the enactment of the forest conservation act, 1980. With the rapid increase in population, demand for timber has increased considerably and is facing severe shortage of the availability of raw material to meet the requirement of many wood based industries.

The demand and supply of timber in India in 2005 was 58 million cubic meters and 29 million cubic meters, respectively which was expected to increase upto 153 million cubic meters and 60 million cubic meters, respectively in 2020 (FSI, 2019). The shortfall of 93 million cubic meters in demand and supply may be due to less forest area coupled with low productivity of Indian forest and this demand of timber can only be met by import from international market. India is likely to face severe shortage of supply of timber to meet its requirement from both domestic and international front. The gap between demand and supply of timber is increasing by alarming proportions day by day. The growing demand for timber can be met to some extent by growing short rotation, fast growing alternative species and by increasing the timber production through intensive management (Saravanan *et al*., 2014).

The choice of timber species for different end uses is changing from durable primary conventional species to short-rotation and fast growing plantation species. The main emphasis behind producing raw material is to shift the source from natural forests to plantation timbers. The choice of such alternative fast growing tree species to suit the raw material requirements of industry is of critical importance to meet out the demand supply gap. Among number of timber species, *Melia dubia* is one of such alternative fast growing species (Saravanan *et al.*, 2014).

Melia dubia Cav. belongs to the family meliaceae has its trade name as Malabar Neem, commonly known as Kadukhajur. It is a large deciduous and fast growing tree commonly found in tropical and sub-tropical regions of India. It is indigenous to Sri Lanka,

Malaysia, Java, China, Australia and Indian sub-continent. In India it is commonly found in Western Ghats of Southern India and moist deciduous forest of Kerala. In Himachal Pradesh the species has been introduced in lower hills mainly in the Hamirpur district (Sharma *et al*., 2018).

Melia dubia has the unique feature of growing upto 30 m with the spreading crown and clear bole of 9 m (Chauhan *et al*., 2018). It grows up to an altitude of 600-1800 m. Due to fast growth rate of the species, multiple uses and high economic returns it is popularly termed as Money-spinning tree. Therefore, the cultivation and utilization of *Melia dubia* is economically viable, ecologically empathetic, environmentally ameliorative and aesthetically acceptable option to the farmers and the industrialists.

Melia dubia timber is an excellent and highly suitable raw material for wood based industries like paper and plywood owing to its natural anti-termite property, high recovery and exceptional fiber strength as compared to traditional raw materials (Swaminathan *et al*., 2012). The wood also find use in construction, agricultural implements, match boxes and furniture. Thus the species has a assured market value due to its multipurpose utilities and is in high demand by the wood based industries. Through effective research programs, the possibility to broaden the market of *Melia dubia* plantation products into specialty products *i.e.* development of higher grade of plywood; Decorative/Marine/Shuttering grade Plywood, Medium Density Fiberboard (MDF), Particle Board, Laminated Veneer Lumber (LVL), Compreg *etc.* is required.

Being a versatile material, the physical, chemical and strength properties of wood vary greatly from species to species, within a species and also within a tree from bottom to top. These variations also occur among genera, among geographic sources within a species, among trees within a geographic source as well as between and within individual trees (Swaminathan *et al.*, 2012). Tree to tree variation in wood properties within a species are large and it may be due to its anisotropic nature and environmental growth conditions (Longuetaud *et al*., 2017). Therefore, better knowledge of variation in wood of a particular species is of utmost value for determining the efficient wood utilization and processing (Koga and Zhang, 2004).

Vertical variation in wood properties within tree species is due to the variation in the proportion of juvenile wood with height which increases from the base of the tree to the top. The vertical variation studies signify the better utilization of wood according to its varying

physical, chemical and strength properties. These wood properties vary from base to top and also determine the factors that influence the workability of wood. This variation is though less studied as it is more complicated and costly than radial variations (Longuetaud *et al*., 2017). At present, very little research work has been performed on these aspects of this species. Therefore, the current research on **"Vertical variation in the physico-chemical and mechanical properties of *Melia dubia* Cav."** has been proposed with the objectives as follows:

Objectives

i) To study the vertical variation in physico-chemical properties of *Melia dubia* wood

ii) To study the vertical variation in strength properties of *Melia dubia* wood

Chapter-2

REVIEW OF LITERATURE

This chapter reviews the relevant and recently available literature pertaining to the current work *i.e.,* **"Vertical variation in physico-chemical and mechanical properties of *Melia dubia* Cav.''.** The relevant information reported by different researchers pertaining to the present work is discussed under the following headings:

2.1 Growth parameters
2.2 Physical wood characteristics
2.2 Chemical wood characteristics
2.3 Mechanical wood characteristics
2.4 Correlation studies

2.1 GROWTH PARAMETERS

The most noticeable effect of growth is increase in the height and diameter of tree. The ability of trees to grow in height and diameter vary with environmental factors and genetic makeup of tree. The bark percentage has always been variable within the tree and between different tree species.

Bhat (1982) studied variation in bark thickness of *Betula pendula* and *B. pubescens* and revealed that bark of *B. pendula* was thicker and heavier than that of *B. pubescens*. The variation in total bark thickness to height level is of about 72.5 per cent in *B. pendula* and 55.8 per cent in *B. pubescens.* He also observed that bark thickness mainly vary with height and diameter of the stem and declined steeply from the base to 2 m height and then more slowly towards the top of the trees.

Bouvet and Bailleres (1995) studied the variation (axially and longitudinally) in bark thickness of the hybrid *E. grandis* × *E. urophylla* along the different bole heights and found a decrease pattern of bark thickness from the base towards the top of tree. The rate of decrease of bark thickness along the stem was higher at the base (up to 40% tree height) and smaller and constant at the top portion of tree.

Quilho *et al.* (2000) investigated variation in bark thickness and anatomical features of fifteen years old tree of *Eucalyptus globulus* at six height levels (DBH, 5, 15, 35, 55 and

75% of total tree height) of tree and revealed a deceasing trend from base to top of the tree in case of bark thickness.

Quilho and Pereira (2001) evaluated bark thickness in fifteen year-old *Eucalyptus globulus* trees from commercial pulpwood plantations at two sites of Portugal and observed a decreasing pattern from the base to the top at different heights within tree. The average bark thickness decreased from 6.5 mm at the base (5% of total tree height) to 1.9 mm at the top (75% of total tree height).

Tewari and Mariswamy (2013) studied bark per cent in Teak of different age groups (11-36 years) and found that bark content ranged from 22.2-54.3 per cent. It was also found that bark per cent decreased with increase in age while, it increased with increase in height.

Eleoterio *et al*. (2015) studied the bark per cent in the longitudinal axis of the Japanese Raisin tree (*Hovenia dulcis*) and revealed that the bark per cent varied along the tree length, tend to decline from base to linearly to the top of the tree.

Aarnio and velling (2017) studied the bark thickness in twenty two year old Silver Birch (*Betual pendula*) growing in Finland at different tree height levels *viz.* 1.3 m was 4.2 and 3.6 m and revealed a decreasing trend from base to top of the tree.

Cardoso and Pereira (2017) evaluated bark thickness and taper in twenty Douglas-fir trees growing in two different sites of Portugal and found that bark was 26-27 mm thick at the stem base and decreased to 3-5 mm at the top, whereas stem wood tapers were on average 15 mm in the lower stem part and 21 mm in the upper part, respectively.

Bisen *et al.* (2018) evaluated physical properties of wood within the candidates plus trees (CPT's) of *Cleistanthus collinus* in Bhandara and Gondia District of Maharashtra and found maximum values for height, bark per cent and diameter were recorded in Murdoli-1 among 20 selected CPT's.

Deepa (2019) studied the vertical variation in growth parameters at different bole height (base, 10, 20, 30, 40, 50, 60, 70, 80 and 90% bole heights) of 29 year old *Acrocarpus fraxinifolius* tree and found a decreasing trend in diameter and bark per cent with increase in height.

Chambyal (2020) studied the variation in diameter and bark per cent along the different stem heights in *Toona ciliata* and reported a decreasing trend in diameter and bark per cent with increase in height.

Bon *et al.* (2020) studied bark thickness in *Acacia* hybrid (*A. mangium x A. auriculiformis*) compared with *A. mangium* planted in Vietnam and revealed that the bark thickness of *Acacia* hybrid (4.6 mm) was higher that of *A. mangium* (4.5 mm).

Aree *et al.* (2021) investigated bark per cent in *Quercus aegilops* at two different heights of tree and found a decreasing trend from base to top of tree. Average bark percent at two different heights varied from 8.22 per cent to 7.53per cent.

2.2 PHYSICAL WOOD CHARACTERISTICS

The properties which can be determined without any change in size, shape and chemical composition of wood are referred to as physical properties. The most important physical properties of wood are density, specific gravity, wood-water relations, shrinkage, swelling and color.

Purkayastha *et al*. (1982) studied the wood properties of *Eucalyptus tereticornis* grown at different sites. The study exhibited a trend of increasing specific gravity from pith to periphery in a linear fashion.

Stringer and Olson (1987) studied within-tree variation (vertically and radially) and between site variation of 10 to 12 year old Black Locust (*Robinia pseudoacacia*) and found that the specific gravity and fibre length increased radially from pith to cambium and the total stem-wood fibre length and specific gravity were averaged 1.05 mm and 0.68, respectively. Sharma (1997) also studied wood properties of Black Locust tree managed under high density plantations and observed that fibre length decreased with increase in stem height.

Ismail *et al*. (1995) studied Kelempayan trees (*Neolamarckia cadamba)* along their radii at five different height levels to evaluate variations of wood anatomical properties and found that vessel proportion increases while ray proportion, fibre diameter and fibre lumen diameter decreases with height. No significant trend was found for fibre length vertically. Vessel proportion, fibre length, fibre wall thickness and ray proportion increased from pith to

bark, while fibre proportion decreased. Within-tree variations are more consistent radially than vertically.

Koubaa *et al*. (1998) examined the variation in fibre length pattern within the stem of *Populus x Eurarnericana* hybrid from a nine year old tree grown at south-central Quebec. Samples were taken from a total of twenty seven trees representing ten clones at four different height and found minimum fibre length at the base of the tree which tended to reach maximum value at mid height of the tree.

Chauhan *et al.* (2001) evaluated interclonal variation in specific gravity of 18 clones of *Populus deltoides* collected from experimental plantations in Uttrakhand and found that specific gravity within clones showed no significant variation. It was also observed that specific gravity increased with increase in age of tree.

Poku *et al.* (2001) investigated physical properties and their variations within the stem of Stinkwood tree *(Petersianthus macrocarpus)* from the forest of Ghana at three different heights (Breast height, 5m and 12m) and found that Fibre length increased rapidly outward from the pith around the region close to the pith (juvenile wood zone) and less rapidly within the portion of wood beyond this region (mature wood zone). It was also found that all wood properties increased from breast height to the top of the tree.

DeBell *et al.* (2002) studied the wood density of nine year old *Populus deltoides* grown in an intensively-cultured silvicultural research plantation in western Washington at two stem heights *i.e.* at 1.5 and 3.0 m and found the values during the first years as 0.37g/cm³ and then decreased to some extent at age of 4 and 5 years and then increased to an average of 0.45g/cm³ at 9 years. They also found that fibre length increased from 0.57 mm at an age of 1 year to nearly 1.0 mm at 9 years.

Guler *et al*. (2007) examined the physical properties of juvenile wood of Black Pine (*Pinus nigra*) which was compared to the mature Black Pine wood and result indicated that the density (20% lower) and shrinkage-swelling properties of juvenile wood were lower than that of mature wood.

Shashikala and Rao (2009) investigated radial and axial variation of specific gravity and certain anatomical properties in twenty-year-old *Eucalyptus citriodora* Hook. plantations and found that specific gravity and anatomical properties differed greatly in both directions. Average specific gravity ranged from 0.666 to 0.711 pith outwards and from 0.762 to 0.728

base upwards and average fibre length ranged from 1062 to 1301 µm and 1211 to 1166 µm in radial and axial directions, respectively. Similarly vessel diameter showed a range of 112 to 151 µm radially and 118 to 141 µm axially. Although the fibre diameter, fibre lumen diameter and wall thickness showed a significant variation.

Izekor *et al.* (2010) studied wood density for 15, 20 and 25 year old *Tectona grandis* wood based on oven dry weight and volume from the Edo State Forestry plantation sites located within the Forest Reserves and found that wood density increased with increase in age from pith to bark while, decrease in wood density from base to top was reported.

Zahabu *et al.* (2015) studied the effect of spacing on physical properties and growth of fourteen year old teak planted at square spacing regimes of 2 m, 3 m, and 4 m at Longuza Forest Plantation, Tanzania and revealed that there was no effect of spacing on density but density values of heartwood proportion increased with increase in spacing and diameter at breast height and total height increased with increased spacing.

Longui *et al.* (2016) studied the specific gravity and anatomical properties of five trees of twenty year old *Astronium graveolens* which were twenty-year-old at four different stem heights, including stem base, 1 m, 2 m and 3 m and revealed that specific gravity was higher at the base of the tree. An increase in ray frequency was also found which contributes in locking of vertical cells and growth rings, thus preventing the stem from easily breaking when bent.

Coral *et al*. (2017) studied within-tree variation in physical properties of eight year old *Guazuma crinita* stem at base, middle and top trees in order to determine wood density and specific gravity and found the highest basic density (459 kg/m^3) from Tournavista provenance. The mean basic density and specific gravity were 430 kg/m^3 and 0.45, respectively.

Kumar *et al*. (2017) investigated physical properties of *Pinus roxburghii* collected from 10 different locations of Himachal Pradesh and revealed highest specific gravity (0.5756) were recorded in Banethi site and lowest (0.527) were recorded in Ghanahatti site.

Bisen *et al.* (2018) evaluated physical properties of wood within the candidates plus trees (CPT's) of *Cleistanthus collinus* in Bhandara and Gondia District of Maharashtra and found highest values of specific gravity, bark per cent, diameter and maximum fibre length of wood in Sonegaon-2 among 20 selected CPT's.

Deepa (2019) studied the vertical variation in physical properties of *Acrocarpus fraxinifolius* at different bole height and reported that specific gravity and fibre length decreased along with bole height in both sapwood and heartwood, while moisture content increased along the bole height.

Custodio *et al.* (2020) evaluate the fibre dimensions of ten trees of *Guazuma crinit*a having age of 5 and 8 years in radial and longitudinal direction and found that fibre length values of both ages are similar while in lumen diameter and fibre diameter, there is increase in values with increase in the age of the tree.

Chambyal (2020) studied the variation in fibre dimensions of *Toona ciliata* from different bole heights and found that the values for fibre length and fibre diameter ranged between 0.96 mm (90%) to 1.09 mm (base) and 0.020 mm (90%) to 0.026 mm (base), respectively. The maximum values of fibre dimensions were found at the base of the tree and showed a decreasing trend from base to height upto top.

Duong and Matsumura (2021) examined cell morphology of 10-year-old *Melia azedarach* L. trees from a state-owned plantation in Thai Binh province, Vietnam. A cross-sectional disc of 30 mm thick was cut from each sample tree at a height 1 and 3 m above the ground. From each disc, pith-to-bark strips were cut to examine cell morphology and all strips were conditioned (temperature 20 ºC and relative humidity 60 %) to a constant weight before commencing experiments. Results indicated that the vessel lumen diameter of the *M. azedarach* trees rapidly increased up to 7^{th} ring from the pith before becoming constant towards the bark both in earlywood and latewood. Earlywood and latewood fibre lumen diameter showed similar values from pith to 6^{th} ring; however, earlywood and latewood fibre lumen diameter demonstrated increasing and decreasing trends, respectively and remaining constant from 7^{th} ring outwards.

2.3 CHEMICAL PROPERTIES

A chemical property is a characteristic that can only be seen when the material changes and a new material are formed. The wood is mainly made up of substances called cellulose, lignin, hemicelluloses and extractives. Cellulose, the major structural unit of wood contributes 40 to 50 per cent of dry weight. Hemicelluloses are a significant component of plant cell wall and intimately associated with cellulose and appear to contribute as a structural component in plants. The lignin accounts for approximately 30 per cent of wood weight

while conferring the rigidity in woods and plants. Extractives are the wood constituents which accounts 5-10 per cent in the wood and can be extracted with solvents.

Campbell *et al.* (1988) examined the chemical properties of heartwood and sapwood in two varieties of Lodgepole Pine *i.e. Pinus latifolia* and *P. murrayana* and found that the heartwood was significantly higher in extractives than the sapwood, whereas the sapwood was significantly higher in holocellulose and alpha-cellulose than the heartwood. The sapwood and heartwood did not differ in pH and lignin content.

Sharma and Sharma (2003) studied the chemical properties of *Eucalyptus camaldulensis* and *E. globulus* and found lignin content of wood decrease, while holocellulose content increase from ground level to the top of the tree. The solubility in 1 per cent NaOH for both the species was recorded as 18 and 15 percent, respectively.

Elmas (2003) evaluated the solubility of the heartwood and sapwood of *Taxus baccata* material which was taken from Demirkoy forest in the Black Sea region of Turkey. Three samples discs were taken from the trees of diameter about 34.5 cm and from different heights *i.e.* butt, 4-5m height and the top of trees. They found that the amount of extractives in the heartwood is substantially higher than the sapwood and it was also found that the cellular wall materials (cellulose, hemicelluloses and lignin), ethanol-benzene, 1 per cent NaOH and hot water solubility of the sapwood were higher than those of the heartwood.

Mahdavi *et al.* (2004) examined the chemical properties from cross sectional discs which were cut at breast height from three 17-year-old trees of *Eucalyptus camaldulensis* grown in Pasand research station in Mazandaran in central-northern Iran and observed that the cellulose, lignin and extractive content (in acetone soluble) was 47.4 per cent, 30.87 per cent and 6.96 per cent, respectively.

Adamopoulos *et al.* (2005) investigated chemical properties from bottom, middle, and top of three mature thirty five to thirty seven year old Black Locust tree discs to determine the variation within the stem. They found that the lignin content in heartwood (25.73%) was greater than in sapwood (18.13%). The hot-water extractive content was also found greater in heartwood than in sapwood, while the reverse occurred for the dichloromethane extractive content. Ash content of both heartwood and sapwood was found to increase in axial direction.

Bautista and Honorato (2006) studied the chemical properties of four Mexican oak species *i.e. Quercus coccolobifolia, Q. durifolia, Q. rugosa and Q. oleoides*. Samples

of sapwood, heartwood and a mixture of sapwood-heartwood were taken from each species and found that cellulose content ranged from 46.18 to 56.94 per cent and ash content ranged from 0.36 to 0.76 per cent. It was also found that extractives content varied between 4.35 to 9.07 per cent for hot water extractives and 1.02 to 4.83 per cent for alcohol benzene.

Guler *et al*. (2007) studied the chemical properties of Black Pine (*Pinus nigra*) juvenile wood in Turkey and found that juvenile wood had higher lignin and lower holocellulose content than matured wood. The extractive content of juvenile wood was also found to be lower than mature wood whereas hot water solubility and 1 per cent NaOH solubility values were found to be lower for juvenile wood.

Arantes *et al*. (2011) examined total lignin content along with their radial and longitudinal variations in wood from a clone of *Eucalyptus grandis* x *E. urophylla* at age of 6 years. Longitudinal samples were taken at 2, 10, 30 and 70 per cent of the commercial height of trees, and radial samples were taken from each longitudinal position and the number of samples taken depends on the diameter of each discs. The results showed that the concentrations of extractives and total lignin in the wood tended to decrease with increasing distance from the pith and tended to increase in portions closer to the tree base.

Shreshta and Budhathoki (2012) studied chemical compositions of *Rhododendron arboreum* wood which was collected from Simak hills (2000m), Baglung, Western Nepal. The samples of wood were taken from young trees (5-6 years old) and the main chemical components were studied and concluded the percentages as: holocelluloses (69.82%), ash content (0.75%), lignin (24.88%), hemicelluloses (22%), and extractives (4.39%). The solubility of different solvents in cold water and hot water was reported as 7.02 per cent and 8.47 per cent, respectively.

Saravanan *et al.* (2013) evaluated the chemical parameters of five *Melia dubia* trees from different age gradation *viz*., one, two, three, four and five year old which was randomly selected from the farm plantations at Kollegal, Samraj Nagar District. One year old *M. dubia* wood sample have recorded lowest alcohol benzene extractives, hot water solubility and 1 per cent NaOH as compared to other age gradations and the five year old wood sample registered highest alcohol benzene extractive, hot water solubility and 1 per cent NaOH. One year old *M. dubia* was found to be superior for its holocellulose content (75.5%) followed by two, three, four and five year old samples. Low lignin content was reported in one year old (24%)

M. dubia compared to five year old (30%) with highest lignin content. Ash content decreases with increase in the age of the *Melia dubia* wood.

Gominho *et al.* (2015) studied the extractive content at different stem heights (0, 5, 10, 15, 20, 25, 35, 45, 50, 60 and 75% of total tree height) of *Eucalyptus globulus* which was harvested from the experimental plantation in Furadour, Portugal and found that the total extractives content decreased till 35 per cent height level and then it was constant upwards. It was also reported that extractives content increased radially from the sapwood to the inner heartwood (6.2 to 12.5% at the base) and Ethanol-soluble compounds were found to be more at the base.

Topaloglus and Erisir (2018) evaluated the holocellulose content of 6 specimens (3 each) of Oriental Beech and Caucasian Fir trees grown at Turkey. The 6 specimens (3 each) were cut at 1.30 m, 6.30 m and 12.30 m tree height. The lowest content of holocellulose in Oriental Beech and Caucasian Fir was 75.28 per cent at 6.30 m and 75.38 per cent at 1.30 m, respectively. While, the holocellulose content of Oriental Beech and Caucasian Fir increased from stem height 6.30 m and 1.30 m, respectively.

Heena *et al.* (2019) evaluated the content of holocellulose and lignin in the wood of Banoak (*Quercus leucotrichophora*) among twenty two provenances of Himachal Pradesh and found significant variation in holocellulose and lignin content in wood samples. Lignin content was found to be maximum in Dhami provenance (28.46 %) and minimum in Jibhi provenance (20.48 %) whereas holocellulose content was found to be maximum in Barog provenance (71.30 %) and minimum in Banikhet provenance (65.31 %).

Hassan (2020) studied the chemical composition of *Albizia lebbeck* trees at five different heights levels (base, 25, 50, 75, and 100%) grown in Egypt and revealed that cellulose and hemicelluloses content decreased at 100 per cent of total tree height, whereas lignin content showed an increase from the base to the top. It was also reported that ash content, total extractives, and the hot water and cold water soluble extractives showed a decreasing trend from the base to the top of the stem.

Chambyal (2020) investigated the variation in chemical properties at different bole height of *Toona ciliata* and found a decreased trend along the bole height from base to top in hot water-soluble extractives, cold water-soluble extractives, alcohol-benzene soluble

extractives and lignin content, whereas the holocellulose content and ash content showed increasing trend along the bole height.

Sunny *et al.* (2020) studied chemical properties of *Artocarpus heterophyllus* from three different zones based on altitudinal classes which are divided into lowland, midland and highland of Thrissur district, Kerala. The wood properties obtained from the analysis at three different zones revealed that the maximum value for cold water soluble extractives and hot water soluble extractives were observed in highland whereas the lowest in lowland. In case of alcohol benzene extractives, the maximum extractives were obtained from lowland and lowest from midland. Holocellulose content was maximum for the wood obtained from midland and lowest for lowland. The ash content was found maximum for midland wood and lowest for highland wood.

2.4 MECHANICAL PROPERTIES

The mechanical properties of wood are those which measure its fitness and ability to resist applied or external forces. Study of the mechanical properties of a material is concerned mostly with its behaviour in relation to stress and strain.

Kliger *et al.* (1998) evaluated Norway Spruce from fast and slow grown stands having diameter range 36-40 cm and age of 65 (fast grown) and 105 (slow grown) and revealed that the bending strength from the slow-grown stand samples was 57 per cent higher and the modulus of elasticity 54 per cent higher than that from the fast-grown stand samples. This increase in mechanical properties from the pith to the bark was far more significant for samples from the slow grown stand than from the fast grown one. It was also found that the higher bending (47%) and modulus of elasticity (30%) values was found on mature wood near the bark than in wood near the pith.

Evans *et al*. (2000) studied the effect of juvenile wood on the mechanical properties of Red Alder (*Alnus rubra*) and found that tree growth in first ten to twenty years had reduced the mechanical strength properties of the tree species. They also reported that strength can be reduced up to 50 per cent by the presence of juvenile wood.

Machado and Cruz (2005) analyzed within-stem variation in mechanical properties of Maritime pine timber and found a decreasing trend in mechanical properties along the stem (from butt to top). An increase in bending strength (55%), modulus of elasticity parallel to

grain (99%), compression strength parallel to grain (44%) and tensile strength perpendicular to grain (27%) was observed at all tree height levels.

Guler *et al.* (2007) studied the mechanical properties of juvenile wood of *Pinus nigra* naturally growing in Duzce and found that compression strength and bending strength ranged between 35-55 and 58-85 N/mm^2 for both properties, respectively. It was also found that the mechanical properties of Black Pine juvenile wood was observed to be lower compared to the mature wood.

Izekor *et al.* (2010) examined the modulus of rupture of *Tectona grandis* wood for age fifteen, twenty and twenty five years. Six trees were selected from each age class from the Edo State Forestry plantation sites located within the Forest Reserves. Wood samples were collected from innerwood, middlewood and outerwood at 10, 50 and 90 per cent of the tree merchantable height. The mean values of modulus of rupture were 76.86, 103.95 and 134.69 N/mm^2, modulus of elasticity were 6846.92, 9920.54 and 12845.57 N/mm^2, compressive strength parallel to grain were 43.74, 58.47 and 75.36 N/mm^2 for age 15, 20 and 25-year old of *Tectona grandis* wood, respectively. It was also found that mechanical properties increased with age and from pith to bark and generally decreased from base to top and also increased from innerwood to outerwood at any particular height.

Olufemi and Malami (2011) studied the density and bending strength of *Eucalyptus camaldulensis* collected from three different geographical locations which vary differently in these sites. A total of 5 trees were selected from each site and found that the average values of static bending strength and the modulus of elasticity (stiffness) were 133.33 N/mm² and 15219.89 N/mm², respectively.

Ali (2011) studied the mechanical properties parameters *viz*., static bending, compression parallel to grain, hardness, compression perpendicular to grain and shear parallel to grain have lower values in both green and air-dry conditions for Jackfruit (*Artocarpus heterophyllus*) wood as compared to teak (*Tectona grandis*).

Zhou *et al.* (2012) studied the mechanical properties of two logs of *Pinus resinosa* obtained from a local sawmill in Fredericton, New Brunswick, Canada and their variation within the stem of the tree. The results indicated that wood mechanical properties *viz,.* tension parallel to the grain, tension perpendicular to grain, shear parallel to grain tend to decrease from top to bottom in the longitudinal direction. Tensile strength parallel-to-grain increased

from pith to bark across the ring because of the correspondingly denser wood. However, for shear strength parallel-to-grain and tensile strength perpendicular-to-grain, strength in tangential direction was slightly higher than in radial direction.

Zahabu *et al.* (2015) studied the effect of spacing on mechanical properties of teak planted at square spacing regimes of 2 m, 3 m, and 4 m at Longuza Forest Plantation, Tanzania and wood properties were studied at age of 14 years in forest plantation and found that all the properties except cleavage tangential to grain were not affected by spacing.

Kiaei and Farsi (2016) examined Persian silk wood (*Albizzia julibrissin*) for modulus of elasticity (MOE) and modulus of rupture (MOR) at different levels of total height (5, 25, 50 and 75%) in both positions along radial direction (heartwood and sapwood) in bending and found a decreasing trend from base to top with height. MOE and MOR along longitudinal position from base to top decreased with height. The mean of MOR and MOE in sapwood are lower compared to the corresponding values for heartwood.

Kumar *et al*. (2017) investigated mechanical properties of *Pinus roxburghii* collected from different locations of Himachal Pradesh and the results revealed highest bending strength and compression parallel to grain (0.0089 KN/mm^2 and 0.057 KN/mm^2, respectively) in Banethi, whereas maximum tensile strength and compression perpendicular to grain were observed in samples collected from Chabbal (0.043KN/mm2) and Nurpur (0.00180 KN/mm2), respectively.

Topaloglus and Erisir (2018) evaluated the compression strength parallel to grain of Oriental Beech and Caucasian Fir trees at different tree heights (1.30 m, 6.30 m and 12.30 m) from discs of 15 cm and found the highest (59.26 MPa) compression strength was at 1.30 m for Oriental Beech and the lowest (33.02 MPa) was at 12.30 m for Caucasian Fir.

Chambyal (2020) studied the vertical variation in mechanical properties at different bole height of *Toona ciliata* and reported that all properties (tensile strength, bending strength, compressive strength parallel to grain, compression strength perpendicular to grain, bending modulus of rupture, modulus of elasticity, compression parallel to grain) had a decreasing trend from bottom to top of the tree.

2.5 SIMPLE CORRELATION

Correlation is a statistic that measures the degree to which two variables move in relation to each other. It is a term that is a measure of the strength of a linear relationship between two quantitative variables and helps in determining both nature and strength of relationship between the two variables. When relation between only two variables is studied it is known as simple correlation.

Jourdain and Olson (1984) analysed *Platanus occidentalis* progeny from 48 half-sib families representing five geographic seed sources for variations in wood properties and growth rate and results showed that diameter, height, volume, specific gravity, fibre length, and moisture content showed significant differences between families. Height and moisture content were the only traits that did not exhibit significant variations due to seed source. The variation in wood properties was much less than that in growth parameters. Diameter, height, and volume were positively correlated with specific gravity and fibre length.

Campbell *et al.* (1988) studied the chemical properties of heartwood and sapwood in both varieties of Lodgepole Pine *i.e. Pinus latifolia* and *P. murrayana* and found that the ash, lignin, and holocellulose content were positively correlated with stem height in *P. latifolia* and *P. murrayana*. Extractive and alpha-cellulose content were negatively correlated with stem height. In contrast, the holocellulose and alpha-cellulose content was 2 per cent higher in *P. murrayana* than in *P. latifolia*.

Zang (2004) studied the relationships between wood specific gravity and mechanical properties (MOR, MOE and Cmax) with growth rate from four distinct wood categories: first softwood category, second softwood category, diffuse-porous wood category and ring-porous wood category (RPC) in sixteen timber species. Statistical results revealed that specific gravity and mechanical properties varied greatly with growth rate as well as in all wood categories. Among the mechanical properties studied, MOE is remarkably less influenced by the growth rate than MOR.

Pinto *et al*. (2004) analysed heartwood and sapwood development with various physical parameters in *Pinus pinaster* on thirty five trees randomly sampled in four sites in Portugal and result showed that physical parameters *viz.,* stem diameter, DBH and tree total height were found to correlate significantly with the heartwood content.

Pan *et al.* (2005) studied the wood anatomical properties of twenty four year old hybrid tulip *(Liriodendron chinense* x *L.tulipifera)* and reported an average fibre length of 0.80-1.74 mm. The fibre length increased rapidly from pith to bark tended to stabilize at the 9th to 11th year growth ring. Basic density, fibre length, and fibre wall thickness were found to have negative relationship with DBH, while fibre width positive relation with DBH. Height of crown had a positive effect on basic density but had no influence on any of the remaining properties.

Okoh (2014) studied correlation between fibre, physical and mechanical properties of Ghanaian hardwoods and found that there was positive correlation between wood density and compression parallel to grain ($R_2 = 0.644$), modulus of rupture ($R_2 = 0.680$) and modulus of elasticity ($R_2 = 0.646$) at four different species level. The significant linear relationship was found between wood density and mechanical strength properties of timber. A positive relationship between wood density and mechanical strength properties was also noticed. The anatomical features (fibre diameter and fibre length) were reported to be weak and negatively correlated.

Riyaphan *et al.* (2015) evaluated the chemical and mechanical properties in *Hevea brasiliensis* and found that hemicellulose, lignin, and pentosan contents were negatively correlated with resistance to cleavage properties and tensile strength. Among mechanical properties, the correlation between MOE and MOR was found significant ($p < 0.01$). Cellulose and static bending (MOR and MOE), cellulose and cleavage, lignin and tensile strength perpendicular to the grain were found to have significant correlation coefficients.

Crespo *et al.* (2020) examined the mechanical properties of *E. globulus* samples from the Galicia region, northwest of Spain and revealed that best correlations between ultimate stress and modulus of elasticity was in bending and tension parallel to the grain, whereas compression tests revealed the lowest correlations between both properties and timber-to-timber friction coefficients resulted lower than those of other species.

Chapter-3

MATERIALS AND METHODS

The present investigations entitled **"Vertical variation in physico-chemical and mechanical properties of *Melia dubia* Cav."** was carried out in the Department of Forest Products, College of Forestry, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP) during 2019-20 and 2020-21. The mechanical testing of the *Melia dubia* wood species was carried out in the Wood Workshop and physico-chemical studies was done in the Departmental Laboratory. The details of the material used, experimental techniques and methods of analysis employed during the course of examination are presented in this chapter as below:

3.1.1 LOCATION

The procurement of wood samples of *Melia dubia* was done from Khaggal Forestry field of College of Horticulture and Forestry, Neri Hamirpur, lies at an altitude of 786 m above mean sea level at Latitude and Longitude of 31°41'38"N and 76°27'25"E, respectively.

3.2.2 METHODOLOGY

The *Melia dubia* tree, of about 3 years old having 18.5 cm DBH and tree height of 9 m (clean bole of 5.5 m) was felled for carrying out studies on vertical variation in wood characteristics. The clean bole of *Melia dubia* was divided into different heights *viz.* base (0), 15, 30, 45, 60, 75 and 90 per cent of total bole height and it was converted into 7 logs each of 75 cm length. From each log, samples of 35 cm length were taken for analysis of physico-chemical and anatomical parameters. The diameter of each log was measured with the help of the tree calliper and bark thickness was measured with a scale. One disc of 5 cm was taken from each log and divided into four equal cleavages, and these were considered as replicates for specific gravity, maximum moisture content, fibre length, fibre diameter, vessel number and vessel diameter. The remaining wood of this disc was grounded separately to form the composite samples. The composite samples were divided into three parts (replication) for chemical analysis. For testing the mechanical properties, the remaining part of the log was converted in the Wood Workshop to prepare samples of following dimensions:

i. 300 mm x 10 mm x 10 mm (Tensile strength)

ii. 300 mm x 20 mm x 20 mm (Static bending)

iii. 50 mm x 20 mm x 20 mm (Compression strength parallel to grain)

iv. 50 mm x 20 mm x 20 mm (Compression strength perpendicular to grain)

The data generated was statistically analysed by using completely randomized block (CRD) design as suggested by Panse and Sukhatme (1978).

3. 3 OBSERVATIONS RECORDED

i) Diameter (cm)

Diameter of the logs was measured in cm with the help of tree calliper. It was measured at two axes which were at right angle to each other.

ii) Bark (%)

Bark was calculated by measuring diameter over bark with the help of tree calliper and diameter under bark with the help of scale in cm. Bark percentage was calculated by the formula as given below:

$$\textbf{Bark (\%)} = \frac{\text{D.O.B - D.U.B}}{\text{D.O.B}} \times 100$$

Where,

D.O.B = Diameter over bark

D.U.B = Diameter under bark

Experiment 1: To evaluate the physico-chemical properties of wood

A. Physical properties

No. of replications = 3

Plate 1: Felling of *Melia dubia* tree

Plate 2: Conversion of *Melia dubia* tree into logs

Plate 3: Discs of *Melia dubia*

Observations recorded

i. Moisture content (MC%)

ii. Specific gravity

iii. Fibre dimensions a) Fibre length (mm)

b) Fibre diameter (mm)

iv. Vessel dimensions a) Vessel diameter (mm)

b) Number of vessels/mm^2

B. Chemical properties

No. of replications = 3

Observations recorded

i. Cold water-soluble extractives (%)

ii. Hot water-soluble extractives (%)

iii. Alcohol-benzene soluble extractives (%)

iv. Holocellulose content (%)

v. Lignin content (%)

vi. Ash content (%)

A. PHYSICAL PROPERTIES

i. Moisture content (MC%)

Fresh weight of the samples was recorded just after they were cut from the logs. After initial weighing, the samples were then oven dried first at 60°C for few hours and then at 102 ± 2°C till constant weight. The moisture per cent of the samples was calculated by using the formula given by Desch and Dinwoodie (1996).

$$\textbf{Moisture content (\%)} = \frac{M_{ini} - M_{od}}{M_{od}} \times 100$$

Where,

M_{ini} = Initial weight of samples (g)

M_{od} = Oven dried weight of sample (g)

ii. Maximum moisture content (MMC %)

Maximum moisture content (MMC%) of the wood samples was determined by the procedure prescribed as per the Indian Standard IS: 1708 (BIS, 1986). Wood samples of size 1cm x 1cm x 1cm were prepared from the disc taken from base of each log. The wood samples were then submerged in distilled water for 7 days to ensure complete saturation. The saturated samples were taken out and weighed. Samples were dried first in air and then at 105 ± 2°C till constant weight. The maximum moisture content (%) was calculated by using the formula as given below:

$$\textbf{Maximum moisture content (MMC\%)} = \left\{ \frac{M_m - M_o}{M_o} \right\} \times 100$$

Where,

M_m = Saturated weight of wood samples (g)

M_o = Oven dried weight of wood samples (g)

iii. Specific gravity

Specific gravity of the samples was determined by the maximum moisture content method (Smith, 1954). Wood samples of the size 1cm x 1cm x 1cm were prepared from the disc which was cut from the base of each log. These samples were submerged in water till saturation and then weights of the samples at this point were recorded as weight at maximum moisture content level. These samples were then oven dried at 102 ± 2°C until a constant weight was attained. The specific gravity was calculated as per the formula given below:

$$\textbf{Specific gravity} = \frac{1}{\frac{M_m - M_o}{M_o} + \frac{1}{GS}}$$

Where,

M_m = Wet weight of the sample (g)

M_o = Oven dried constant weight of the sample (g)

GS = Average density of wood substance, a constant, having value 1.53

iv. Fibre dimensions (mm)

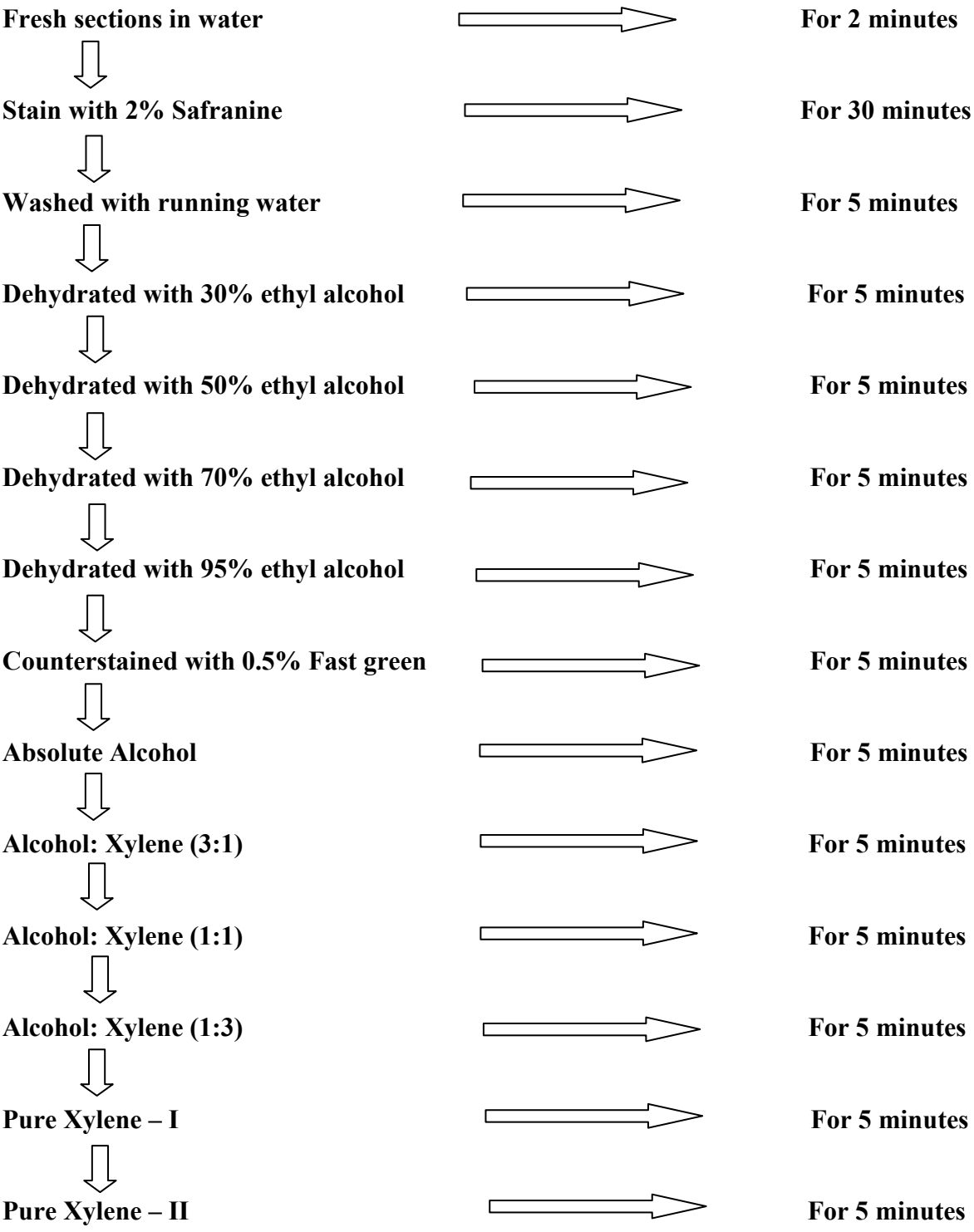
The fibre dimensions (fibre length and fiber diameter) were determined by macerating the wood shavings in Jeffery's solution, *i.e*. 10 per cent chromic acid and 10 per cent nitric acid, for 48 hours (Pandeya *et al.* 1968). Thereafter, the shavings were thoroughly washed with distilled water, stained with Saffranine and teased in order to separate the fibres with the help of needle in 10 per cent glycerin prior to mounting on slides with cover slip. The straight and complete fibers were selected and measured under a Stereo Microscope equipped with a 15X eyepiece. About 4-5 measurements of fibers were made in each slide using an Ocular Micrometer fitted to the eyepiece of a microscope at 4X magnification and standardized with the help of Stage Micrometer. Ten observations for each replicate were recorded for each parameter and the average was recorded as mean value for each replicate.

v. Vessel dimensions (mm)

Wood samples of size 5 cm x 2cm x 2cm were prepared for determination of vessel dimensions (vessel diameter and number of vessels) and submerged in water for three days to soften them for studying smooth cutting. Thin microscopic sections were cut with the help of sliding microtome for vessel dimensions. The well stained permanent slides of sections were made as per the procedure outlined by Johansen (1940). Measurement of vessel dimensions was done by using an ocular micrometer fitted in the eyepiece of a microscope at 15X magnification with 10X magnification of objective lens which was standardized with the help of stage micrometer. Diameter (mm) of the vessels was measured on the transverse sections (TS) with the help of Ocular Micrometer. Ten observations from each replication of specific site were taken. All variable sized vessels were taken as observations.

PREPARATION OF SAMPLES FOR VESSEL DIMENSIONS

The radial sections of wood were cut with a sliding microtome (Model: RMT-45) at 10–20 μm thickness. These were viewed under the microscope and only the selected sections were used for preparation of permanent slides. For better contrast and tissue identification, sections were stained as per schedule described by Johansen (1940).



Flow chart showing outline of staining procedure

a) Number of vessels per mm^2

The transverse sections (TS) of the wood samples were used to determine the frequency of vessels per sq. mm which was calculated by counting the number of vessels in randomly taken area per microscopic field by using the formula given below (Anoop *et al.*, 2014).

$$\textbf{Number of Vessel} = \frac{\text{Number of vessels}}{\text{Area in sq. Millimeters}} \text{ X } 10^6$$

Area of microscopic field under microscope with eyepiece at 15X magnification and 10X magnification of objective lens was calculated as:

Firstly correction factor (CF) was calculated by using Ocular Micrometer fitted in 15X eye piece and 10X objective lens.

One division of stage micrometer equals 0.01mm.

Step 1 – Coincide the ocular scale with stage micrometer where it was found that: 100 division of stage micrometer scale (S) = 117 division of ocular scale (O)

Step 2 – Calculation for Correction factor (CF)

100 (S) = 117 (O)

Correction factor S/O = 100/117

CF= 0.8547 x 0.01 (one division of stage micrometer is equal to 0.01mm)

CF= 0.00855 mm

Step 3 – Calculation of the area of observed field under microscope using ocular scale

Diameter of observed field (d) = 0.93

Radius (r) = 0.93/2

(r) = 0.465 mm

Area of observed field (πr^2) = π x 0.465 x 0.465 = 0.6789 mm^2

Step 4 – Calculations for number of vessels per mm^2 / number of vessels per field

If X= 0.6789

Y= 1 mm^2

$$Y\ (0.6789) = X\ (1mm^2)$$

$$Y = \frac{(X)\ (1mm^2)}{0.6789}$$

$$Y = 1.4721\ (X)$$

Where,

Y = number of vessels per mm^2

X = number of vessels per field

B. CHEMICAL PROPERTIES

Analysis of the chemical composition included: determination of cold water, hot water and alcohol-benzene soluble extractives, holocellulose, lignin and ash content. Preparation of samples for analysis of chemical composition was done by using TAPPI (Technical Association Pulp and Paper Industry) standard methods. The wood samples were chipped and grounded using Wood Grinder.

i) Cold water-soluble extractives (%)

Two gram of oven dried coarsely ground wood was weighed and put into a conical flask containing 300 ml of double distilled water. The mixture was then allowed to digest at room temperature with frequent stirring for 48 hours. The material was then filtered through IG-1 Crucible and washed thoroughly with cold double distilled water and dried to a constant weight in an oven at 105 ± 2°C. The cold-water solubility was determined by calculating the loss in weight of sample taken and was expressed as percentage on the basis of oven dry weight of wood (T1m-59-Anonymous, 1959a).

ii) Hot water-soluble extractives (%)

Two gram of oven dried coarsely ground wood was taken in a flask having 100 ml of double distilled water fitted with reflux condenser. It was digested on boiling water bath for 3 hours. The contents were then filtered through IG-1 Crucible and residue was dried in oven at 105 ± 2°C till constant weight. The solubility was determined by calculating the loss in weight of the sample taken and expressed as percentage (T1m-59-Anonymous, 1959a).

iii) Alcohol-benzene soluble extractives (%)

Ten gram of oven dried coarsely ground wood was placed in a porous thimble (oven dried and weighed). The thimble was placed in a Soxhlet Apparatus and extracted with 200 ml of alcohol-benzene (1:2 v/v) for 6 hours. The porous thimble was then taken out and allowed to dry in open air and finally in an oven at 105 ± 2°C till constant weight is attained. The alcohol-benzene solubility was determined by calculating the loss in weight of the sample taken and expressed in percentage (T6m-59-Anonymous, 1959b).

iv) **Holocellulose content (%)**

Five gram of oven dried sample pre-extracted with alcohol-benzene (1:2 v/v) was taken in a conical flask and 160 ml of distilled water was added to it. The contents were treated with 1.5 g of Sodium Chlorite and 10 drops of Acetic Acid at 70-80°C on a water bath for one hour. The process was repeated four times till the meal became white. The contents were then filtered through IG-2 Crucible, washed with water and finally with Acetone. The sample was dried in an oven at 105 ± 2°C until a constant weight. The extracted holocellulose content was calculated on the basis of the oven dry weight (T9m-59-Anonymous, 1959).

v) Lignin content (%)

Two gram of oven dried sample pre-extracted with alcohol-benzene (1:2 v/v) was treated with 15 ml of 72 per cent Sulphuric Acid for 2 hours at 18-20°C with constant stirring. The material was brought down to 3 per cent by adding 545 ml of double distilled water. The solution was refluxed for 4 hours and then allowed to settle. The contents were filtered and washed with hot distilled water. The material was then dried in an oven at 105 ± 2°C till constant weight was obtained and the extracted lignin content was calculated on the basis of the oven dry weight and expressed in percentage (T12m-59-Anonymous, 1959c).

vi) Ash content (%)

Two gram of oven dried wood sample was placed in a Silica Crucible. The crucible was then placed in a furnace at 575 ± 25°C for a period of three hours, to burn off all the carbon. The completion of ignition was indicated by the absence of black particles. The Crucible was then

removed from the furnace and cooled to room temperature and ash content was weighed and percentage was calculated.

Experiment 2: To study the strength properties of wood

i) Tensile strength (kN/mm^2)

The standard size of the specimen for conducting the tensile test was 300 mm x 10 mm x 10 mm. The computer-generated data and graph were drawn by using Universal Testing Machine (UTN-10), so as to derive the values of maximum load, maximum displacement and breaking pattern for all the samples. Proper care was taken, so that each specimen faced similar type of test measures.

Modulus of elasticity in Tensile strength (MPa)

Tensile strength data and graph were used for the determination of modulus of elasticity in tensile strength. It was calculated by using load and displacement at limit of proportionality as follows:

$$\textbf{Modulus of Elasticity (MOE)} = \frac{PL}{\Delta A}$$

Where,

P = Load at limit of proportionality in N

L = Gauge length of the specimen in mm

Δ = Displacement at limit of proportionality in mm

A = Cross- sectional area in mm^2

ii) Bending strength (kN/mm^2)

The standard size of the specimen taken was 300 mm x 20 mm x 20 mm which was tested for bending strength on Universal Testing Machine (UTN-10) and data was recorded for each sample. All care was taken so that each specimen faced similar type of test measures.

Bending modulus of rupture (MPa)

Bending strength data and graph were used to determine bending modulus of rupture. It was calculated by using the following formula:

$$\textbf{Modulus of Rupture (MOR)} = \frac{3PL}{2bh^2}$$

Where,

P	=	Load at limit of proportional
L	=	Gauge length of the test specimen in mm
b	=	Breadth of the test specimen in mm
h	=	Depth of the test specimen in mm

Modulus of elasticity in Bending strength (MPa)

The static bending strength data and graph were used for the determination of bending modulus of elasticity. It was calculated using load and displacement at limit of proportionality as follows:

$$\textbf{Modulus of Elasticity (MOE)} = \frac{PL^3}{4\Delta bh^3}$$

Where,

P	=	Load at limit of proportionality in kN
L	=	Gauge length of the specimen in mm
Δ	=	Displacement at limit of proportionality in mm
b	=	breadth of the specimen in mm
h	=	height/depth of the specimen in mm

iii) Compression strength

a) Compression strength parallel to grain (kN/mm^2)

This test was done in the direction along the grain and the data was generated in the computer software programme. The standard size of specimens for compression parallel to grain test was 50 mm x 20 mm x 20 mm.

Modulus of elasticity in compression strength parallel to grain (MPa)

The compressive strength data parallel to grain and graph were used for the determination of modulus of elasticity. It was calculated using load and displacement at limit of proportionality as follows:

$$\textbf{Modulus of elasticity (MOE)} = \frac{PL}{\Delta A}$$

Where,

P = Load at limit of proportionality in N

L = Gauge length of the specimen in mm

Δ = Displacement at limit of proportionality in mm

A = Cross- sectional area in mm^2

b) Compression strength perpendicular to grain (kN/mm^2)

The specimen size of 50 mm x 20 mm x 20 mm was taken across the direction of grain for carrying out this test. The data recorded in computer was used for further analysis and comparison.

Modulus of elasticity in compression strength perpendicular to grain (MPa)

The compressive strength data perpendicular to grain and graph were used for the determination of modulus of elasticity. It was calculated using load and displacement at limit of proportionality as follows:

$$\textbf{Modulus of Elasticity (MOE)} = \frac{PL}{\Delta A}$$

Where,

P = Load at limit of proportionality in N

L = Gauge length of the specimen in mm

Δ = Displacement at limit of proportionality in mm

A = Cross-sectional area in mm^2

3.4 STATISTICAL ANALYSIS

The recorded data were subjected to Completely Randomized Block Design analysis as described by Panse and Sukhatme (1978) and Chandel (1984).

i) Analysis of variance (ANOVA)

The analysis of variance table was set up as under:

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares	Variance ratio
Treatment	(t-1)	S_t^2	M_t	M_t/M_e
Error	t(r-1)	S_e^2	M_e	
Total	(r x t)-1			

Where,

r = Number of replications

t = Number of treatments

S_t^2 = Sum of squares due to treatment

S_e^2 = Sum of squares due to error

M_t = Mean sum of square due to treatment

Me = Mean sum of square due to error

The Critical Difference (CD) was calculated as follows:

$CD = SE(d) \times t_{0.05}$

Where,

SE (d) = Standard Error of Difference was calculated as

SE (d) = $\sqrt{2Me/r}$

$t_{0.05}$ = t value at 5 per cent Degree of Freedom

ii) Simple correlation coefficients

Simple Correlation Coefficient (Karl Pearson's) between two characters was worked out by using the following formula as given by (Panse and Sukhatme, 1978).

$$r\,(XY) = \frac{Cov\,(X,Y)}{\sqrt{VarX.VarY}}$$

Where,

r (XY)	=	Simple correlation between X and Y
V(X)	=	Variance of X characters V(Y)

Chapter-4

RESULTS AND DISCUSSION

The results obtained from the present investigations entitled **"Vertical variation in physico-chemical and mechanical properties of *Melia dubia* Cav.",** carried out in the Laboratory and Wood Workshop of the Department of Forest Products, College of Forestry, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP) during 2019-20 and 2020-21 are presented in this chapter. The data obtained from the study were subjected to appropriate statistical analysis and the results are presented and discussed under the following main headings:

4.1 Growth parameters

4.2 Physico-chemical properties

4.3 Strength properties

4.4 Correlation studies

4.1 GROWTH PARAMETERS

4.1.1 Diameter (cm)

The data pertaining to diameter of *Melia dubia* along with the bole height are presented in Table 1. The perusal of data revealed significant variation for diameter. Among all the bole heights, the maximum diameter was observed at base (20.66 cm) which was statistically at par with 15 per cent (19.10 cm) and minimum was noticed at 90 per cent (14.43 cm) of total bole height which was statistically at par with 60 per cent and 75 per cent heights having values of 15.38 cm and 14.53 cm, respectively.

Diameter growth of a particular tree is mainly due to the cell divisions in the cambium layer of the bark and has revealed a significant variation with bole height. The variation has showed decreasing trend with increase in height due to more lateral meristem growth at the base as compared to height upto top. Diameter growth of a tree has also been affected by various environmental and edaphic factors prevailing in that locality. These results are in conformity with Chambyal (2020) in *Toona ciliata*, Deepa (2019) in

Acrocarpus fraxinifolius and Hemilton *et al.* (2007) in *Eucalyptus globulus*, Longui *et al.* (2016) in *Astronium graveolens* and Sharma (1997) in *Robinia pseudoacacia.*

4.1.2 Bark (%)

The data observed for bark percentage revealed a significant variation along the bole height of tree (Table 1). The maximum bark per cent was observed at base (2.35%) which was statistically at par with 15 per cent (2.19%) and minimum was noticed at 90 per cent (1.76%) which was statistically at par with 30 per cent (1.95%), 45 per cent (1.87%), 60 per cent (1.80%) and 75 per cent (1.80%) of total bole height of tree.

The bark is formed as a result of the secondary growth in the plants. Bark formed in younger wood is usually thinner than the mature wood which is found at the base of the stem. Countless aspects of the environment have also influenced the evolution and development of the tree bark. Quilho *et al.* (1999) have studied within tree variability of bark thickness in *E. globulus* and found an age effect in periderm and phloem development with an increase of periderm (especially of phelloderm) and of non collapsed phloem at the stem base as compared with the younger samples in the upper part of the tree. In the present study bark thickness has showed a decreased trend from base to the top and similar results have been reported by Chambyal (2020) in *Toona ciliata*, Deepa (2019) in *Acrocarpus fraxinifolius*, Sharma and Sharma (2005) and Stringer and Olson (1985) in *Robinia pseudoacacia*, Bhat (1982) in *Betula pendula* and *B. pubescens*, Eleoterio *et al*. (2015) for *Hovenia dulcis* and Bramhall *et al*. (1977) in *Tsuga heterophylla* and Periz and Kanninen (2003) in young and mature *Tectona grandis*.

Table 1: Variation in diameter and bark at different heights of *Melia dubia*

Treatment (%)	Diameter (cm)	Bark (%)
Base	20.66	2.35
0-15	19.10	2.19
15-30	17.49	1.95
30-45	16.24	1.87
45-60	15.38	1.80
60-75	14.53	1.80
75-90	14.43	1.76
Mean	**16.84**	**1.96**
SE (d) ±	**0.47**	**0.08**
$CD_{0.05}$	**1.03**	**0.19**

4.2 PHYSICO-CHEMICAL PROPERTIES

4.2.1 Moisture content (MC%)

The results elucidated in Table 2 revealed significant variation in moisture content in the samples collected within the tree from bottom to top. The highest percentage was recorded in samples collected at 90 per cent (75.34%) of total bole height which was statistically at par with 75 per cent (71.06%), whereas the lowest percentage was found in samples from the base (62.79%) which was statistically at par with 15 per cent (64.09%) and 30 per cent (65.66%) of total bole height.

The amount of water contained in wood is usually expressed as percentage of its oven-dry weight and is termed as moisture content. The water in wood is held in cell wall and cellular cavities as bound water and free water. The moisture content in living trees vary by species and this variation in the moisture content along the tree height may be due to the presence of live tissues, micro-climate and other site factors. Moisture content is found to decrease from base to top and these findings are in conformity with Deepa (2019) in *Acrocarpus fraxinifolius*, Sharma and Sharma (2005) in *Robinia pseudoacacia*, Hashemi and Kord, (2011) for *Cupressus sempervirens*, Dhiman (2018) in *Toona ciliata* and Getahun *et al.* (2014) in *Pinus patula*.

4.2.2 Maximum moisture content (MMC%)

The results presented in Table 2 depicted significant variation in maximum moisture content within the tree from bottom to top. The highest value of maximum moisture content (229.31%) was recorded in samples collected at 90 per cent of total bole height which was statistically at par with 75 per cent (213.20%), whereas the lowest (182.85%) was found in samples from the base which was statistically at par with 15 per cent (192.37%) of total bole height.

Wood is naturally hygroscopic and the extent of its hygroscopicity is defined by cellular components of the wood. The moisture content of wood is at its maximum when the cell walls are completely saturated and the cell cavities are filled with water. Variation in the maximum moisture content along the tree height may be due to the presence of sapwood, live tissues, locality factors and seasons of felling. In the present study, decreasing trend has been found from base to top in maximum moisture content and these findings are in line with Kumar *et al.* (2018) for *Melia dubia* of range 164.1-217 per cent, Hashemi and Kord (2011)

for *Cupressus sempervirens,* Dhiman (2018) in *Toona ciliata* and Getahun *et al.* (2014) in *Pinus patula*.

4.2.3 Specific gravity

The perusal of data in Table 2 revealed significant difference in specific gravity along the total bole height of tree. The maximum value of specific gravity was recorded in samples collected from the base (0.403) of the tree which was statistically at par with 15 per cent (0.388) of total bole height. The minimum value was noticed in samples at 90 per cent (0.339) of total bole height of tree.

Table 2: Variation in moisture content, maximum moisture content and specific gravity of *Melia dubia*

Treatment (%)	Moisture content (%)	Maximum moisture content (%)	Specific gravity
Base	62.79	182.85	0.403
0-15	64.09	192.37	0.388
15-30	65.66	194.06	0.386
30-45	66.54	200.13	0.377
45-60	68.37	205.24	0.370
60-75	71.06	213.20	0.359
75-90	75.34	229.31	0.339
Mean	**67.69**	**202.46**	**0.375**
SE (d) ±	**1.43**	**4.82**	**0.007**
$CD_{0.05}$	**3.09**	**10.4**	**0.015**

Specific gravity is the parameter which determines the strength properties and compactness of wood. The specific gravity of wood is strongly influenced by the vessel-to-fibre ratio, as well as the diameter and wall thickness of fibres (Narasimhamurthy *et al.* 2017). Decreasing trend for specific gravity has been found from base to top of the tree and this variation in specific gravity could be due to the complex interactions among many factors including site, climate, geographic location, age, position in stem growth rate and auxin gradient formation (Poku *et al*. 2001). Similar results have been recorded by Adebawo *et al*. (2019) in *Boscia angustifolia,* Ayarkwa (1998) in *Pterygota macrocarpa*, Longui *et al.* (2016) for *Astronium graveolens* and Zhou *et al*. (2012) for *Pinus resinousa*, Rueda and Eilliamson (1992) in *Ochroma pyramidale*, Lei *et al.* (1996) for *Quercus garryana,* Shashikala and Rao (2009) in *Eucalyptus citriodora,* Chambyal (2020) for *Toona ciliata* and Deepa (2019) in *Acrocarpus fraxinifolius*.

4.2.4 Fibre length (mm)

A critical scrutiny of data revealed non-significant difference in fibre length measured for different bole heights (Table 3). It ranged from 1.007 mm to 0.947 mm.

The variability in anatomical properties has a profound influence on strength properties of wood. Juvenile wood present at the top of the trees consist of shorter fibre as compared to the mature wood present at bottom. Longer fibres present at the base of the tree may be due to greater cambium maturity at the base of the tree (Santos *et al*., 2011). The findings are in line with Narasimhamurthy *et al.* (2017) in *Melia dubia*, Shashikala and Rao (2009) in *Eucalyptus citriodora* wood, Swaminathan *et al.* (2012) in *Melia dubia,* Lachenbruch *et al.* (2011) in various woody plants and Rajput *et al.* (2008) in *Prosopis specigera*.

4.2.5 Fibre diameter (mm)

The values obtained for this parameter are depicted in Table 3 showed significant difference in fibre diameter recorded from different bole heights. The maximum value of fibre diameter was observed at the base (0.0263 mm) which was statistically at par with 15 per cent (0.0257 mm) and 30 per cent (0.0243 mm) and the minimum value for fibre diameter was recorded at 90 per cent (0.0227 mm) which was statistically at par with 45, 60 and 75 per cent with values 0.0240 mm, 0.0233 mm and 0.0230 mm, respectively of total bole height.

Table 3: Variation in fibre length and fibre diameter of *Melia dubia*

Treatment (%)	Fibre length (mm)	Fibre diameter (mm)
Base	1.007	0.0263
0-15	0.973	0.0257
15-30	0.970	0.0243
30-45	0.963	0.0240
45-60	0.957	0.0233
60-75	0.953	0.0230
75-90	0.947	0.0227
Mean	**0.97**	**0.0242**
SE (d) ±	**0.038**	**0.001**
$CD_{0.05}$	**NS**	**0.002**

Fibres are the principal elements responsible for the mechanical support to the tree (Panshin and Zeeuw, 1980). A decreasing trend in fibre diameter has been recorded from base to top which may be due to many molecular and physiological changes that occur in the vascular cambium as well as the increase in the wood cell wall thickness during tree ageing

process (Plomion *et al.,* 2001; Roger *et al.,* 2007). Current findings are in concurrence with studies of Narasimhmurthy *et al.* (2017) in *Melia dubia* and Quilho *et al*. (2000) in *Eucalyptus globulus*, Shashikala and Rao (2009) in *Eucalyptus citriodora* wood.

4.2.6 Vessel diameter (mm)

The data observed for vessel diameter showed non-significant differences and are presented in Table-4. The value of vessel diameter ranged from 0.231 mm to 0.218 mm along the total bole height of the tree.

Vessels are unique features of hardwoods which are designed to perform the function of conduction of water and mineral nutrients in the living trees (Panshin and Zeeuw, 1980; Carlquist, 1984). Variation in vessel diameter from bottom to the top shows a decreasing trend which probably occurs in response to change in site conditions and moisture availability having impact on the physiology of the trees maximum cell wall thickness at base and decreasing upward. Similar results have been reported by Narasimhamurthy *et al.* (2017) in *Melia dubia* and 3 clones of *Populus deltoides* and Longui *et al.* (2017) in *Handroanthus ochraceus* and *H. vellosoi* wood.

4.2.7 Number of vessels/mm^2

The data on number of vessel for *Melia dubia* wood samples procured from different bole heights are presented in Table-4. The maximum number of vessels were found at base (9.671/mm^2) of tree which was statistically at par with 15 per cent (9.432/mm^2), 30 per cent (9.341/mm^2), while the minimum number of vessels was found at 90 per cent (8.864 /mm^2) bole height which was statistically at par with 45 per cent (9.181/mm^2), 60 percent (8.949/mm^2) and 75 percent (8.921/mm^2) bole heights.

Vessels form an efficient system for transporting water (including necessary minerals) from the root to the leaves and other parts of the tree (Panshin and Zeeuw, 1980; Carlquist, 1984). Vessels are also important from timber utilization point of view. Vessel morphology study of *Melia dubia* has revealed diffuse porous vessel arrangement. In the present study significant variation in number of vessels have been found among different bole heights of the tree may be due change in site conditions and moisture availability having impact on the physiology of the trees. The same results have been reported by Saravanan *et al.* (2013) in *Melia dubia*, Florsheim *et al.* (1999) in *Myracrodruon urundeuva*, Bendtsen *et al.* (1981) in *Populus hybrid* and Sahu (2005) in *Samanea saman*.

Table 4: Variation in vessel diameter and number of vessels of *Melia dubia*

Treatment (%)	Vessel diameter (mm)	Number of vessels/mm^2
Base	0.231	9.671
0-15	0.230	9.432
15-30	0.221	9.341
30-45	0.221	9.181
45-60	0.220	8.949
60-75	0.219	8.921
75-90	0.218	8.864
Mean	**0.223**	**9.194**
SE (d) ±	**0.005**	**0.176**
$CD_{0.05}$	**NS**	**0.382**

4.2.8 Cold water-soluble extractives (%)

The data pertaining to cold water-soluble extractives of samples collected from different bole height are presented in Table-5. The maximum percentage was found at the base (5.71%) which was statistically at par with 15 per cent (5.65%), 30 per cent (5.60%) and 45 per cent (5.33%), while minimum percentage was observed at 90 per cent (3.83%), which was statistically at par with 60 per cent (4.80%) and 75 per cent (4.63%) of total bole height.

Cold water solubility of wood represents the solubility of low molecular weight compounds and polysaccharides which are generally sugars, salts, tannins and gums. The species containing large amount of extractives have better durability and dimensional stability. In the present study, more accumulation of cold-water soluble extractives are found more at the base of the tree and decrease upwards. This findings are in conformity with the studies conducted by Hassan (2020) while working on *Albizia lebbeck* wood and Lourenco *et al.* (2008) in *Acacia mealnoxylon*, Chambyal (2020) in *Toona ciliata*, Deepa (2019) in *Acrocarpus fraxinifolius*, Miranda *et al*. (2011) in Teak, Guler *et al.* (2007) in *Pinus nigra* and Gominho *et al*. (2015) in *Eucalyptus grandis* x *Eucalyptus urophylla* hybrids.

4.2.9 Hot water-soluble extractives (%)

The perusal of data in Table 5 depicted a significant variation for hot water-soluble extractives at different bole heights. The maximum value for hot water-soluble extractives was recorded from base (8.56%) which was statistically at par with 15 per cent of total bole height having values of 8.43 per cent. The minimum value was noticed at 90 per cent (6.20%) which was statistically at par with 75 (6.28%) per cent of total bole height.

Hot-water extraction eliminates greater quantities of materials which generally consist of tannins, gums, sugars and salts in addition with phenols that are accumulated more at the base of the tree (Shebani *et al.* 2008). The variation in solubility is due to hydrolysis and corresponding increase in solubility of wood substance during boiling with water. Hillis (1987) has observed that extractive components in wood tend to be higher in heartwood. The top portion of tree contains less heartwood and less extractive than the base of the tree. The hot water-soluble extractives in these results were observed to be more at the base than at the top of the tree. Present results are in line with the results reported by Hassan (2020) in *Albizia lebbeck*, Chambyal (2020) in *Toona ciliata*, Deepa (2019) in *Acrocarpus fraxinifolius*, Elmas in (2003) *Taxus baccata* and Stafasani *et al*. (2018) in *Quercus cerris*.

4.2.10 Alcohol-benzene soluble extractives (%)

The data obtained for alcohol-benzene soluble extractives are presented in Table 5 and significant variation was noted for different bole heights. The maximum percentage was observed at base (10.10%) which was statistically at par with 15 and 30 per cent with values 9.88 and 9.61 per cent, respectively and the minimum percentage was found at 90 per cent (8.01%) which was statistically at par with 75 per cent (8.32%) of total bole height.

Table 5: Variation in cold water-soluble extractives, hot water-soluble extractives and alcohol-benzene soluble extractives of *Melia dubia*

Treatment (%)	Cold water-soluble extractives (%)	Hot water-soluble extractives (%)	Alcohol-benzene soluble extractives (%)
Base	5.71	8.56	10.10
0-15	5.65	8.43	9.88
15-30	5.60	7.83	9.61
30-45	5.33	7.15	9.31
45-60	4.80	7.01	8.77
60-75	4.63	6.28	8.32
75-90	3.83	6.20	8.01
Mean	**5.08**	**7.35**	**9.14**
SE (d) ±	**0.45**	**0.25**	**0.21**
$CD_{0.05}$	**0.97**	**0.55**	**0.46**

Alcohol-benzene solubility of wood is an important factor representing the extractives present in wood which affect the pulping quality. The alcohol-benzene soluble extractives includes tannins, gums, sugars, salts, phenols in addition with oleoresins, fats, waxes and oils, all these are accumulated in the heartwood portion that is more at the base of the tree than at the top. This group of extractives is responsible for various functions including defense

mechanism against microbial attack, tree metabolism and energy reserves. The extractives content of juvenile wood was found to be lower than that of mature wood which is found at the base of the tree. The results have show inverse relationship with height of the tree. The similar findings are in line with the results reported by chambyal (2020) in *Toona ciliata*, Deepa (2019) in *Acrocarpus fraxinifolius*, Stringer and Olson (1987) in *Robinia pseudoacacia* and Gominho *et al*. (2015) in *Eucalyptus grandis* x *E. urophylla* hybrids.

4.2.11 Holocellulose content (%)

A critical scrutiny of data revealed significant variation in samples collected from different bole heights (Table 5). The maximum value was observed at 90 per cent (71.26%) which was statistically at par with 60 and 75 per cent of values 70.12 and 70.53 per cent whereas the minimum value was noticed at base (68.40%) which is statistically at par with 15 (68.60%) and 30 (69.49%) per cent.

Holocellulose is defined as the total polysaccharide fraction of lignocellulosic biomass which is composed of cellulose and all of the hemicelluloses. The holocellulose content of wood is a quantitative indicator that influences pulp suitability considerations of fibrous raw materials. Holocellulose content increase with bole height may be due to the higher percentage of hemicelluloses in the juvenile wood which is present more at the top portion of the tree. Variations in holocellulose content for different tree heights can be related to varying environmental conditions as well as genetic composition differences in a tree. The present findings for holocellulose content have revealed an increasing trend from bottom to height upto top. These findings are also in agreement with those reported by Campbell *et al*. (1990) while working with Lodgepole Pine, Deepa (2019) in *Acrocarpus fraxinifolius*, Chambyal (2020) in *Toona ciliata*, Adamopoulos *et al.* (2005) in *Robinia pseudoacacia*, Zobel and Sprague (1998) in juvenile woods of various forest trees species, Topaloglu and Erisir (2018) in Oriental Beech and Caucasian Fir and Silva *et al*. (2005) in *Eucalyptus grandis*.

4.2.12 Lignin content (%)

The results for this parameter is presented in Table 5 have been revealed a significant difference for mean values of lignin content per cent along total bole height at 5 per cent level of significance. The maximum value was found at the base (26.66%) which was statistically at par with 15, 30 and 45 per cent with values of 26.56, 26.35 and 25.35 per cent, respectively

and the minimum value was observed at 90 per cent (25.08%) which was statistically at par with 60 (25.30%) and 75 per cent (25.23%) of total bole height.

Lignin is a polyphenolic compound having similar proportion to hemicellulose in woody tissues and accounts upto 30 per cent of some secondary cell walls (Scheller and Ulvskov, 2010). Lignin contributes to the rigidity and hydrophobic nature of specialized cells provides mechanical support and carries out water transport. Incorporation of lignin into wood cells provides tree with increased compression strength properties and is responsible for cementing cellulose microfibrils together. Lignin content is higher at the base of the stem and decreases towards top which may be due to more wood maturation and lignification occurring at the bottom of the tree rather than the top. The similar results have been reported by Adamopoulos *et al.* (2005) in *Robinia pseudoacacia*, Raiskila *et al.* (2007) in *Picea abies*, Arantes *et al*. (2011) in *Eucalyptus grandis* x *Eucalyptus urophylla* clone and Ogunjobi *et al*. (2014) in *Vitex doniana*.

4.2.13 Ash content (%)

The data on ash content along the total bole height are presented in Table 5 and has show significant variation within the tree. The highest value for ash content was observed at 90 per cent (2.63%) height which was statistically at par with 75 per cent with values 2.53 per cent and minimum value of (1.88%) was found at the base which was statistically at par with 15 per cent with values 1.90 per cent.

Wood ash is the residue produced due to combustion of wood and other wood waste materials (chips, saw dust, bark, etc.) which mainly consists of organic and inorganic minerals that the trees have absorbed over their lifetime. The results showed an increase in ash content along bole height is probably due to higher proportion of sapwood at the top of tree and more accumulation of nutrients like K and P. In addition, content of the inorganic elements is also greater in sapwood. This trend along the bole heights of tree has also been observed by Chambyal (2020) in *Toona ciliata*, Deepa (2019) in *Acrocarpus fraxinifolius,* Adamopoulos *et al*. (2005) and Stringer and Olson (1987) in *Robinia pseudoacacia*, Guler *et al.* (2007) in *Pinus nigra*, Campbell *et al*. (1990) in Lodgepole Pine and Dibdiakova *et al*. (2017) in Birch wood.

Plate 4: Holocellulose and Lignin

Plate 5: Determination of ash content in *Melia dubia*

Table 6: Variation in holocellulose content, lignin content and ash content of *Melia dubia*

Treatment (%)	Holocellulose content (%)	Lignin content (%)	Ash content (%)
Base	68.40	26.66	1.88
15	68.60	26.56	1.90
30	69.49	26.35	2.06
45	70.06	25.58	2.13
60	70.12	25.30	2.35
75	70.53	25.23	2.53
90	71.26	25.08	2.63
Mean	**69.78**	**25.83**	**2.21**
SE (d) ±	**0.51**	**0.56**	**0.07**
$CD_{0.05}$	**1.12**	**1.08**	**0.15**

4.3 STRENGTH PROPERTIES

4.3.1 Tensile strength (kN/mm^2)

The data on tensile strength exhibited a significant variation in wood samples from different bole heights of presented in Table 6. The maximum tensile strength was recorded from base (0.072 kN/mm^2) which was statistically at par with 15, 30 and 45 per cent with values 0.069, 0.056 and 0.054 kN/mm^2, respectively. The minimum tensile strength (0.039 kN/mm^2) was observed at 90 per cent of total bole height and was statistically at par with 60 per cent (0.050 kN/mm^2) and 75 per cent (0.049 kN/mm^2) of total bole height.

Tensile strength is the ability of wood to withstand a pulling (tensile) force which is capable of breaking many strands of the wood sample. The ability to resist breaking under tensile stress is one of the most important and widely measured properties of wood used for structural applications. The variation in tensile strength for different height along the stem can be due to various environmental factors, genetic structure, size of cells, chemical composition of cell wall, degree of polymerisation and crystallisation of cellulose. The strength of wood also has direct relation with density of the wood. Present findings show a decrease trend in tensile strength along the total bole height and these findings have been found to be in conformity with the work of Chambyal (2020) in *Toona ciliata*, Deepa (2019) in *Acrocarpus fraxinifolius*, Zhou *et al*. (2012) in *Pinus resinosa* and Brunetti *et al*. (2001) in *Cedrus atlantica*.

4.3.2 Bending strength (kN/mm^2)

Perusal of the data in Table 7 revealed non-significant differences on bending strength of wood samples procured from different heights of the tree. The value of bending strength was ranged from 0.009 to 0.008 kN/mm^2 along the total bole height of the tree.

Bending strength is a property of wood fibres to resist the forces that bend the wood and makes it suitable for construction purposes. Under the effect of wind acting on the crown, greater stress occurs at the base resulting in development of wood of higher strength at the base (Ayarkwa, 1998). The variation in bending strength from base to top of the tree may be due to the presence of knots, cellular compositions, cell wall depositions, extractives, and even varying growth characteristics and these variations in values are in line with Chambyal (2020) in *Toona ciliata*, Deepa (2019) in *Acrocarpus fraxinifolius*, Machado and Cruz (2005) in *Pinus pinaster*, Zeidler *et al*. (2015) in *Abies grandis* and Venson *et al.* (2008) in *Melia azedarach*.

Table 7: Variation in tensile strength and bending strength of *Melia dubia*

Treatment (%)	Tensile strength (kN/mm^2)	Bending strength (kN/mm^2)
Base	0.072	0.009
15	0.069	0.009
30	0.056	0.009
45	0.054	0.008
60	0.050	0.008
75	0.049	0.008
90	0.039	0.008
Mean	**0.055**	**0.008**
SE (d) ±	**0.008**	**0.000**
$CD_{0.05}$	**0.018**	**NS**

4.3.3 Compression strength parallel to grain (kN/mm^2)

Compression strength parallel to grain has shown statistically significant variation along the bole height of the tree (Table 8). The highest value of compressive strength parallel to grain was found at base (0.039 kN/mm^2) and the lowest (0.033 kN/mm^2) value of compression strength parallel to grain was noticed at 90 per cent of total bole height which was statistically at par with 15 per cent, 30 per cent, 45 per cent, 60 per cent and 75 per cent bole heights with values 0.035, 0.034, 0.033, 0.033 and 0.033 kN/mm^2, respectively.

Plate 6: Tensile strength testing

Plate 7: Failure in tensile strength

Wood is a versatile material that may be subjected to a variety of forces during its use. As a result, determining the maximum compressive strength of wood is important for its end uses. Compression parallel to grain can be defined as a force which is applied at both ends of wood to compress the wood fibres (Rowell, 2013). Compression of wood depends upon the porosity of wood and its cellular compositions. The wood is generally stronger in the direction parallel to the grain than perpendicular to grain because the cells are aligned in this direction (Yadavrao, 2018). In the present study compression strength parallel to grain has shown decreasing trend from base upwards. Similar results have been reported by Mahmud *et al*. (2017) in *Neolamarckia cadamba*, Izekor *et al.* (2010) in *Tectona grandis*, Awan *et al.* (2012) in *Cedrus deodara*, Machado and Cruz (2005) for Maritime Pine timber (*Pinus pinaster*) and Pikk and Kask (2004) in the wood of *Pinus sylvestris*.

4.3.4 Compression strength perpendicular to grain (kN/mm^2)

The data on compression strength perpendicular to grain exhibited a significant variation in wood samples from different bole heights (Table 8). The critical scrutiny of the data revealed the highest compression strength perpendicular to grain for wood samples from base (0.039 kN/mm^2) of total bole height which was statistically at par with 15 per cent of total bole height with value 0.026 kN/mm^2. The lowest compression strength perpendicular to grain was noticed at 90 per cent (0.012 kN/mm^2) bole height which was statistically at par with 30, 45, 60 and 75 per cent with values 0.021, 0.018, 0.014 and 0.013 kN/mm^2, respectively.

Table 8: Variation in compression strength parallel to grain and compression strength perpendicular to grain of *Melia dubia*

Treatment (%)	Compression strength parallel to grain (kN/mm^2)	Compression strength perpendicular to grain (kN/mm^2)
Base	0.039	0.039
15	0.035	0.026
30	0.034	0.021
45	0.033	0.018
60	0.033	0.014
75	0.033	0.013
90	0.033	0.012
Mean	**0.034**	**0.020**
SE (d) ±	**0.001**	**0.006**
$CD_{0.05}$	**0.002**	**0.013**

The force exerted perpendicular to the length of wood cells is referred as compression perpendicular to grain (Rowell, 2013). The present study has revealed that compression perpendicular to grain has shown a decreasing trend with tree height and this variability in the results may be attributable to the fact that cellular arrangement perpendicular to the grain weakens the wood under compression since cell layers in this direction may have different cell types. Present investigations are in line with the findings of Shukla and Kamdem (2008) in Red pine (*Pinus resinosa*), Izekor *et al*. (2010) in *Tectona grandis*, Rosner and Karlsson (2011) in Norway spruce (*Picea abies*), Aydin *et al.* (2007) in Poplar, Fir and hornbeam and Juodeikiene and Norvydas (2005) in Oak and Ash wood.

4.3.5 Bending modulus of rupture (MPa)

The data obtained on bending modulus of rupture (Table 9) revealed significant variation along the bole height of the tree. The maximum (0.182 MPa) bending modulus of rupture was observed in wood samples collected from 30 per cent bole height and the minimum value (0.171 MPa) was observed in the samples procured from 60 per cent bole height of tree.

Table 9: Variation in bending modulus of rupture of *Melia dubia*

Treatment (%)	Bending modulus of rupture (MPa)
Base	0.181
15	0.181
30	0.182
45	0.176
60	0.171
75	0.176
90	0.174
Mean	**0.177**
SE (d) ±	**0.005**
$CD_{0.05}$	**NS**

The Modulus of Rupture (MOR) is a measure of wood sample strength before it rupture. It measures the wood ultimate strength and it can also be used to assess the maximum fibre strength of wood at its failure. The significant variation has been recorded in modulus of rupture for different bole heights and this may be due to varying growth characteristics and locality factors. Present results of bending MOR are in conformity with the findings of Deepa (2019) in *Acrocarpus fraxinifolius*, Rao *et al.* (1972) in *Dalbergia sissoo,* Kiaei and Farsi (2016) in wood of Persian silk and Langum *et al*. (2009) in Douglas-Fir and Western Hemlock.

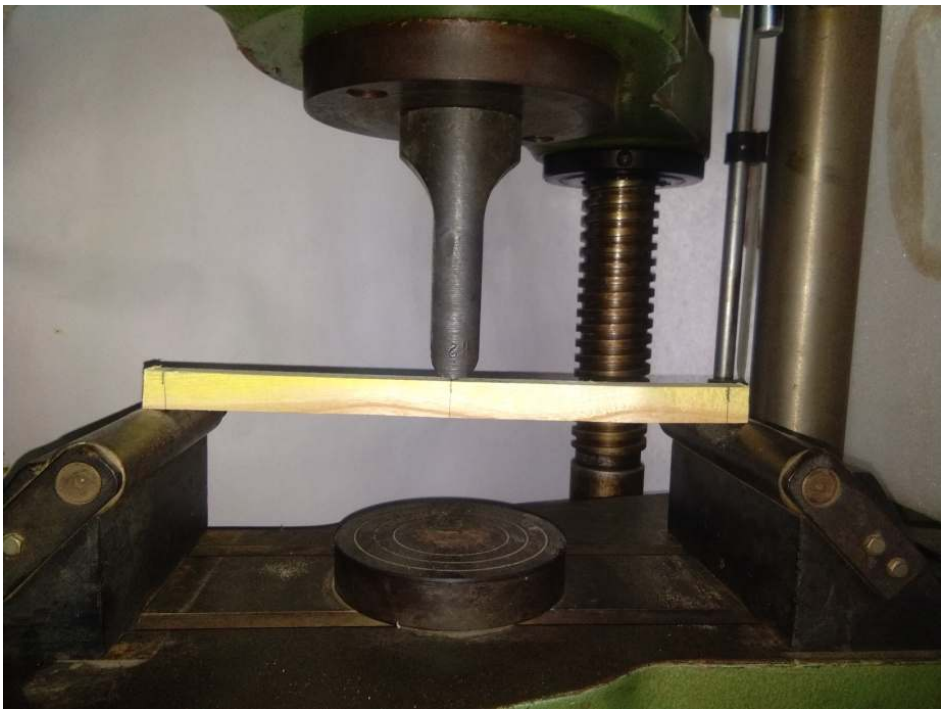


Plate 8: Bending strength testing

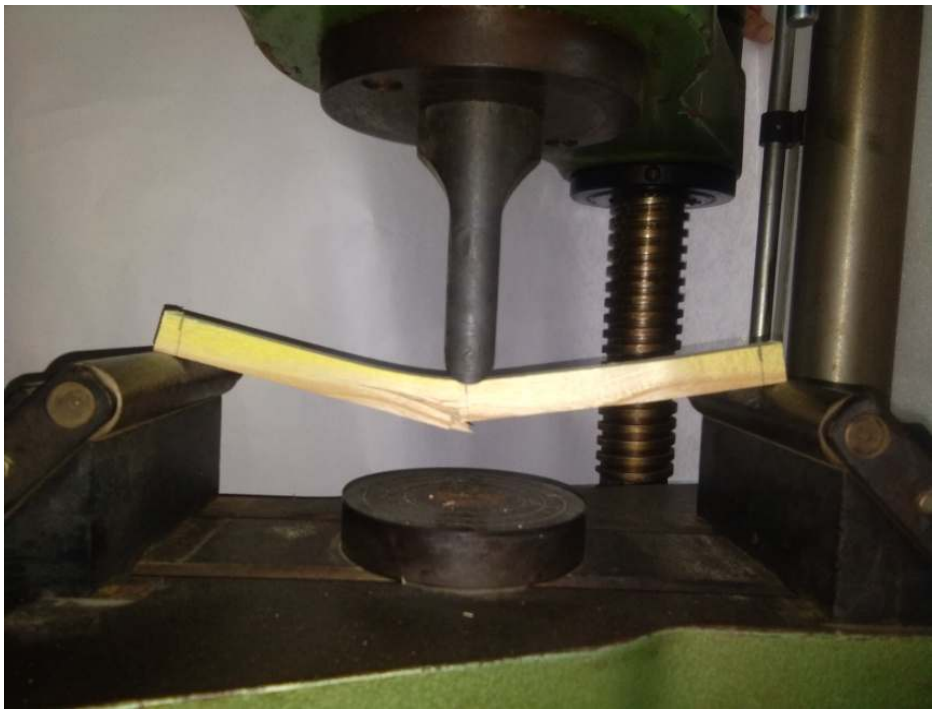


Plate 9: Failure in bending strength

4.3.6 Modulus of elasticity in tensile strength (MPa)

The data pertaining to modulus of elasticity in tensile strength of *Melia dubia* wood samples procured from different bole heights are presented in Table-10. The data showed a significant variation for different bole height at 5 per cent level of significance. The highest value for modulus of elasticity in tensile strength was recorded in wood collected from 30 per cent (1.423 MPa) which was statistically at par with 45 per cent of value 1.303 MPa and lowest value was observed at 60 per cent (0.556 MPa) which was statistically at par with 15, 75 and 90 per cent of values 0.788, 0.755 and 0.740 MPa, respectively.

The modulus of elasticity is a measurement of the resistance of wood to being elastically deformed when a stress is applied to it. The modulus of elasticity in tensile strength of wood fibres depicts its capability to resist the forces pulling it apart. The current study has shown variation in MOE, which may be attributed due increments of growth rings and the addition of more mature wood and cambial age, and other various site factors (Izekor *et al*. 2010). Deepa (2019) in *Acrocarpus fraxinifolius*, Sunny (2017) in *Dalbergia sissoo*, Heena (2014) in *Salix* and Thakur (2017) in *Acacia nilotica* have also revealed similar results.

4.3.7 Modulus of elasticity in bending strength (MPa)

The critical analysis of data pertaining to modulus of elasticity in bending strength is presented in Table 10 showed significant variation at 5 per cent level of significance. The maximum modulus of elasticity in bending strength was recorded at 90 per cent (9.327 MPa) which was statistically at par with 60 per cent (8.927 MPa) and minimum was observed at 45 per cent (7.156 MPa) which was statistically at par with base (7.445 MPa) and 15 per cent (7.576 MPa), respectively.

Significant variation within the tree for bending modulus of elasticity was observed along the tree height. This variation may have been due to various factors like age, rate of growth and the chemical composition of the tree. Similar results have been observed by Bruechert *et al*. (2000) in Norway spruce (*Picea abies*), Missanjo and Matsumura (2016) in *Pinus kesiya,* Langum *et al*. (2009) in Douglas-Fir and Western Hemlock, Kiaei (2011) in Elm (*Zelcova carpinifolia*) and Kiaei and Farsi (2016) in Persian Silk wood.

Table 10: Variation in modulus of elasticity in tensile strength and modulus of elasticity in bending strength of *Melia dubia*

Treatment (%)	Tensile modulus of elasticity (MPa)	Bending modulus of elasticity (MPa)
Base	0.970	7.445
15	0.788	7.576
30	1.423	8.082
45	1.303	7.156
60	0.556	8.927
75	0.755	8.094
90	0.740	9.327
Mean	**0.962**	**8.087**
SE (d) ±	**0.169**	**0.417**
$CD_{0.05}$	**0.367**	**0.903**

4.3.8 Modulus of elasticity in compression strength parallel to grain (MPa)

Modulus of elasticity in compression strength parallel to grain has shown significant variation along the bole height of the tree and is presented in Table 10. The maximum value was noticed at base (0.625 MPa) which was statistically at par with 15 per cent with value of 0.514 MPa of total bole height, while minimum value was recorded at 60 per cent (0.337 MPa) which was statistically at par with 30 per cent (0.432 MPa) 75 per cent (0.429 MPa) and 90 per cent (0.458 MPa).

Modulus of elasticity (MOE) measures the stiffness of wood and is a good indicator of its maximum strength. Applied stresses from this type of compressive strength parallel to grain are generally considered consistent across the entire cross-section of the wood sample, and the fibres are uniformly stressed parallel to the grain along the full length of the wood sample. It is the ratio of stress placed upon the wood compared to the strain (deformation) that the wood exhibits along its length. In the present study, it has been revealed that their is a significant variation with tree bole height which may be due to genetic factors, site environmental factors, increments of growth rings and more mature wood addition with age. The results were also in line with the finding of Deepa (2019) in *Acrocarpus fraxinifolius,* Duong and Matsumura (2018) in *Melia azedarach* and Fuwape and Fabiyi (2003) in *Nauclea diderichii* wood.

4.3.9 Modulus of elasticity in compression strength perpendicular to the grain (MPa)

The perusal of data on the modulus of elasticity perpendicular to grain (Table 11) has showed a significant variation along the bole height at 5 per cent level of significance. The

Plate 10: Compression parallel to grain testing

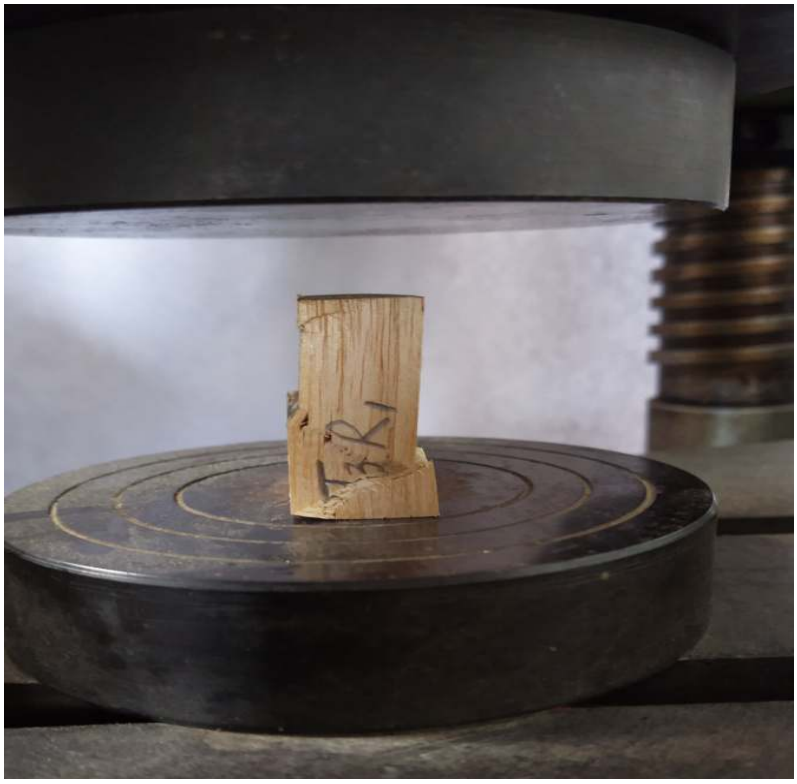


Plate 11: Failure in Compression Parallel to Grain

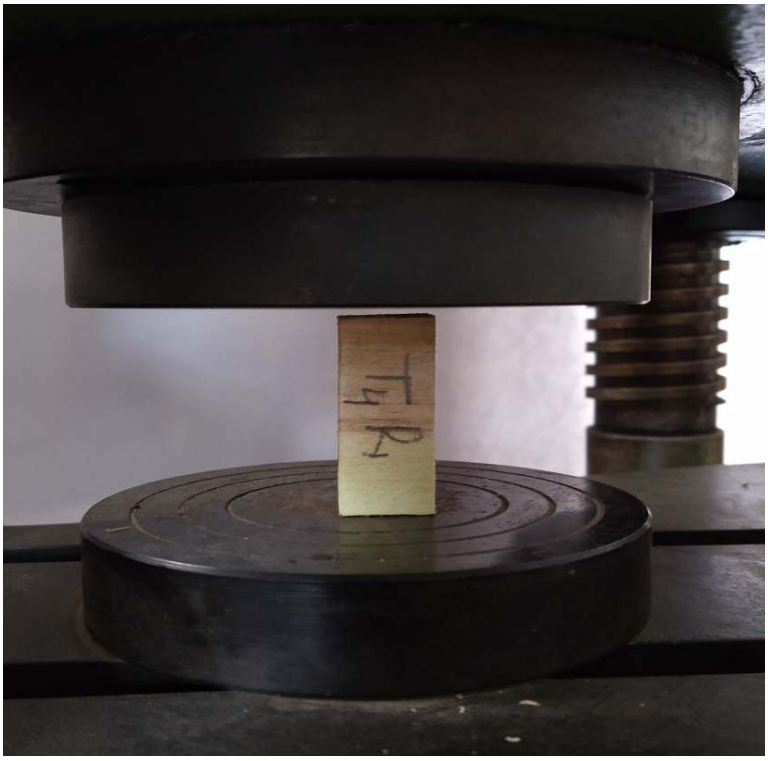


Plate 12: Compression perpendicular to grain testing

Plate 13: Failure in compression perpendicular to grain

maximum modulus of elasticity perpendicular (0.078 MPa) to grain was recorded at 90 per cent bole height and the minimum value (0.034 MPa) was observed at 15 per cent which was statistically at par with base, 15, 45, 60 and 75 per cent with values of 0.042, 0.037, 0.041, 0.042 and 0.035 MPa, respectively of total bole height.

Table 11: Variation in modulus of elasticity in compression strength parallel to grain and modulus of elasticity in compression strength perpendicular to grain of *Melia dubia*

Treatment (%)	Modulus of elasticity in compression strength parallel to grain (MPa)	Modulus of elasticity in compression strength perpendicular to grain (MPa)
Base	0.625	0.042
15	0.514	0.037
30	0.432	0.034
45	0.474	0.041
60	0.337	0.042
75	0.429	0.035
90	0.458	0.078
Mean	**0.467**	**0.044**
SE (d) ±	**0.056**	**0.011**
$CD_{0.05}$	**0.121**	**0.024**

The data have revealed significant variation in modulus of elasticity compression parallel to grain along with bole height. This may be due to when all fibres are crushed together, the stresses can be increased again, making it impossible to establish a failure level as the wood is compressed. The present results are similar to the findings of Deepa (2019) in *Acrocarpus fraxinifolius*, Chambyal (2020) in *Toona ciliata* and Fuwape and Fabiyi (2003) in *Nauclea diderichii* wood. Zelalem *et al*. (2014) also recorded significant variation in Modulus of elasticity (MOE) in *Pinus patula.*

4.4 CORRELATION STUDIES

4.4.1 Simple correlation coefficient between physical and chemical properties of *Melia dubia*

The values calculated for simple correlation coefficient between physical and chemical properties of *Melia dubia* is presented in Table 11. Among 78 combinations of simple correlation, 48 combinations were found to be highly significant out of which 33 were positively correlated and 15 were negatively correlated at 1 per cent level of significance.

i) Moisture content (MC%)

Moisture content was found positively correlated with holocellulose content (0.740) and ash content (0.742) at 1 per cent level of significance, while it was negatively correlated with specific gravity (-0.991), fibre length (-0.990), fibre diameter (-0.561) vessel diameter (-0.561), number of vessels (-0.565), hot water soluble extractives (-0.598), cold water soluble extractives (-0.588), alcohol-benzene soluble extractives (-0.590) and lignin content (-0.742) at 1 per cent level of significance.

ii) Specific gravity

Specific gravity was positively correlated with fibre length (0.998), fibre diameter (0.563), vessel diameter (0.562), number of vessels (0.566), hot water soluble extractives (0.600), cold water soluble extractives (0.589), alcohol-benzene soluble extractives (0.591) and lignin content (0.742) at 1 per cent level of significance, while negative correlation was found with holocellulose content (-0.740) and ash content (-0.742) at 1 per cent level of significance.

iii) Fibre length (mm)

Fibre length was found to be positively correlated with fibre diameter (0.564), vessel diameter (0.563), number of vessels (0.567), hot water soluble extractives (0.601), cold water soluble extractives (0.590), alcohol-benzene soluble extractives (0.592) and lignin content (0.743), while negative correlation was found with holocellulose content (-0.740) and ash content (-0.743) at 1 per cent level of significance.

iv) Fibre diameter (mm)

Fibre diameter was found to have positive correlation with vessel diameter (0.996), number of vessels (0.996), hot water soluble extractives (0.996), cold water soluble extractives (0.996) and alcohol-benzene soluble extractives (0.997) at 1 per cent level of significance, whereas the values of the rest of the correlation coefficients were observed to be non-significant.

v) Vessel diameter (mm)

Vessel diameter was found to have positive correlation with number of vessels (0.996), hot water soluble extractives (0.997), cold water soluble extractives (0.997) and

alcohol-benzene soluble extractives (0.997) at 1 per cent level of significance, whereas non-significant correlation was found with holocellulose content , lignin content and ash content.

vi) Number of vessels/mm^2

Number of vessels was found positively correlated with hot water soluble extractives (0.997), cold water soluble extractives (0.997) and alcohol-benzene soluble extractives (0.997) and at 1 per cent level of significance, while non-significant correlation was found with holocellulose content, lignin content and ash content.

vii) Cold water-soluble extractives (%)

Cold water-soluble extractives were positively correlated with alcohol-benzene soluble extractives (0.998) at 1 per cent level of significance. Non-significant correlation was observed with holocellulose content, lignin content and ash content.

viii) Hot water-soluble extractives (%)

Hot water soluble extractives were positively correlated with cold water soluble extractives (0.998) and alcohol-benzene soluble extractives (0.999) at 1 per cent level of significance. The correlation coefficients with holocellulose content, lignin content and ash content were recorded to be non-significant.

ix) Alcohol-benzene soluble extractives (%)

Alcohol-benzene soluble extractives were found to have non-significant correlation with holocellulose content, lignin content and ash content.

x) Holocellulose content (%)

Holocellulose content was observed to have positive correlation value with ash content (0.995) and negative correlation with ash content (-0.996) at 1 per cent level of significance.

xi) Lignin content (%)

Lignin content was observed to have negative correlation with ash content (-0.999) at 1 per cent level of significance.

Table 12: Simple correlation coefficients between physical and chemical properties of *Melia dubia*

	Moisture content (%)	Specific gravity	Fibre length (mm)	Fibre diameter (mm)	Vessel diameter (mm)	Number of vessel /mm^2	Hot water-soluble extractives (%)	Cold water-soluble extractives (%)	Alcohol-benzene soluble extractives (%)	Holocellulose content (%)	Lignin content (%)	Ash content (%)
Moisture content (%)	1.000	-0.991*	-0.990*	-0.561*	-0.561*	-0.565*	-0.598*	-0.588*	-0.590*	0.740*	-0.742*	0.742*
Specific gravity		1.000	0.998*	0.563*	0.562*	0.566*	0.600*	0.589*	0.591*	-0.740*	0.742*	-0.742*
Fibre length (mm)			1.000	0.564*	0.563*	0.567*	0.601*	0.590*	0.592*	-0.740*	0.743*	-0.743*
Fibre diameter (mm)				1.000	0.996*	0.996*	0.996*	0.996*	0.997*	-0.110	0.105	-0.109
Vessel diameter (mm)					1.000	0.996*	0.997*	0.997*	0.997*	-0.112	0.106	-0.111
Number of vessel/mm^2						1.000	0.997*	0.997*	0.997*	-0.107	0.102	-0.106
Hot water-soluble extractives (%)							1.000	0.998*	0.999*	-0.063	0.056	-0.060
Cold water-soluble extractives (%)								1.000	0.998*	-0.075	0.070	-0.074
Alcohol-benzene soluble extractives (%)									1.000	-0.075	0.070	-0.075
Holocellulose content (%)										1.000	-0.996*	0.995*
Lignin content (%)											1.000	-0.999*
Ash content (%)												1.000

* Correlation is significant at the 0.01 level (2-tailed)

4.4.2 Simple correlation coefficient between strength properties of *Melia dubia*

The recorded values for simple correlation coefficients for strength properties are presented in Table 12. Among total 36 combinations, 18 combinations were found to be highly positively correlated at 1 per cent level of significance and 9 combinations were highly negatively correlated at 5 per cent level of significance.

i) Tensile strength (kN/mm^2)

Tensile strength showed positive and highly significant correlation coefficient values for bending strength (0.995), compression strength parallel to grain (0.994), compression

strength perpendicular to grain (0.852) bending modulus of rupture (0.851) and modulus of elasticity in tensile strength (0.867) at 1 percent level of significance, while it was found negatively correlated with modulus of elasticity in compression strength parallel to grain (-0.454), modulus of elasticity in compression strength perpendicular to grain (-0.456) and modulus of elasticity in bending strength (-0.439) at 1 per cent level of significance.

ii) Bending strength (kN/mm^2)

Bending strength was observed to have significant positive correlation coefficient with compression strength parallel to grain (0.995), compression strength perpendicular to grain (0.877) bending modulus of rupture (0.872) and modulus of elasticity in tensile strength (0.895) at 1 per cent level of significance, whereas it was found negatively correlated with modulus of elasticity in compression strength parallel to grain (-0.454), modulus of elasticity in compression strength perpendicular to grain (-0.456) and modulus of elasticity in bending strength (-0.440) at 1 per cent level of significance.

iii) Compression strength parallel to grain (kN/mm^2)

Compression strength parallel to the grain was observed to be positively correlated with compression strength perpendicular to grain (0.869), bending modulus of rupture (0.850) and modulus of elasticity in tensile strength (0.881) at 1 per cent level of significance, negative correlation was found with modulus of elasticity in compression strength parallel to grain (-0.455), modulus of elasticity in compression strength perpendicular to grain (-0.456) and modulus of elasticity in bending strength (-0.440) at 1 per cent level of significance.

iv) Compression perpendicular to grain (kN/mm^2)

Compression strength perpendicular to the grain was observed to be positively correlated with bending modulus of rupture (0.947) and modulus of elasticity in tensile strength (0.984) at 1 per cent level of significance. The values for rest of the correlation coefficients were observed to be non-significant.

v) Modulus of elasticity in tensile strength (MPa)

Modulus of elasticity in tensile strength was found to be non-significant with all the parameters studied and had a negative non-significant correlation with bending modulus of elasticity, modulus of elasticity in compression parallel to grain and modulus of elasticity in compression perpendicular to grain.

vi) Modulus of elasticity in bending strength (MPa)

Modulus of elasticity in bending strength was found to have significant positive correlation with modulus of elasticity in compression parallel to grain (0.973) and modulus of elasticity in compression perpendicular to grain (0.945) at 1 per cent level of significance.

vii) Modulus of elasticity in compression parallel to grain (MPa)

Modulus of elasticity in compression parallel to grain showed positive correlation with modulus of elasticity in compression perpendicular to grain (0.931) at 1 per cent level of significance.

Table 13: Simple correlation coefficients between strength properties of *Melia dubia*

	Tensile strength (kN/mm^2)	Bending strength (kN/mm^2)	Compression strength parallel to grain (kN/mm^2)	Compression strength perpendicular to grain (kN/mm^2)	Bending modulus of rupture (kN/mm^2)	Modulus of elasticity in tensile strength (MPa)	Modulus of elasticity in bending strength (MPa)	Modulus of elasticity in compression parallel to grain (MPa)	Modulus of elasticity in compression perpendicular to grain (MPa)
Tensile strength (kN/mm^2)	1.000	0.995*	0.994*	0.852*	0.851*	0.867*	-0.439*	-0.454*	-0.456*
Bending strength (kN/mm^2)		1.000	0.995*	0.877*	0.872*	0.895*	-0.440*	-0.454*	-0.456*
Compression strength parallel to grain (kN/mm^2)			1.000	0.869*	0.850*	0.881*	-0.440*	-0.455*	-0.456*
Compression strength perpendicular to grain (kN/mm^2)				1.000	0.947*	0.984*	-0.111	-0.116	-0.120
Bending modulus of rupture (kN/mm^2)					1.000	0.960*	-0.092	-0.096	-0.104
Modulus of elasticity in tensile strength (MPa)						1.000	-0.143	-0.151	-0.156
Modulus of elasticity in bending strength (MPa)							1.000	0.973*	0.945*
Elasticity in compression parallel to grain (MPa)								1.000	0.931*
Modulus of elasticity in compression perpendicular to grain (MPa)									1.000

***Correlation is significant at the 0.01 level (2-tailed).**

Correlation is a measure of association between two variables. Analysis of correlation reveals about the extent to which the concerned variables are related. Correlation is said to be simple correlation when the relation between two variables is studied and from these two variables one is independent and the other is secondary or dependent. The relationship studied between physico-chemical and strength properties of wood is shown in Tables 12-13.

Various physico-chemical properties have been studied for simple correlation. The fibre length has been found to have positive correlation with fibre diameter, vessel diameter and number of vessels. The similar findings were also reported by Saravanan *et al.* (2013) in *Melia dubia.* The hot water soluble extractives have been found to be strongly positively correlated with cold water soluble extractives, alcohol-benzene soluble extractives and lignin content. Similar results have also been reported by Nimkar (2002) in *Pinus roxburghii*. Holocellulose has shown highly significant and negative correlation with lignin content and it is also in conformity with findings of Lekha (2012) in *Acacia catechu*, Deepa (2019) in *Acrocarpus fraxinifolius* and Silva *et al*. (2005) in *Eucalyptus*. Latib (2014) in *Neolamarckia cadamba* has observed highly significant and negative correlation between specific gravity and moisture content.

In the present study, mechanical properties of *Melia dubia* have shown relation with each other along the tree height. Riyaphan *et al.* (2015) in *Hevea brasiliensis* reported significant correlation between MOR and MOE. Okon (2014) has also found negative relation between modulus of elasticity and compression parallel to grain in *Gmelina arborea*. Kloiber *et al.* (2013) in Spruce, Fir and Pine; Kiaei and Farsi (2016) in Persian Silk wood and Hernandez *et al*. (1998) in Poplar hybrid clones reported similar results. Tensile strength has found positive correlation values with compression parallel to grain and modulus of elasticity in tensile strength. Similar findings have also been supported by Elzaki and Khider (2013) in *Cupressus lusitanica*.

Chapter-5

SUMMARY AND CONCLUSION

The present investigation entitled "**Vertical variation in physico-chemical and mechanical properties of *Melia dubia* Cav."** was carried out in the Department of Forest Products, College of Forestry, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP) during 2018-19 and 2019-20. The present study was carried out with the following objectives.

i) To study the vertical variation in physico-chemical properties of *Melia dubia* wood

ii) To study the vertical variation in strength properties of *Melia dubia* wood

To achieve these objectives, *Melia dubia* tree was felled and was divided into 7 different heights *viz.* base (0), 15, 30, 45, 60, 75 and 90 per cent of total bole height and finally into desired dimensions as per the test specifications so as to examine the physical, chemical and mechanical properties of the wood at different bole heights. The results observed from the study are summarized as under:

5.1 GROWTH PARAMETER

Among different bole heights of *Melia dubia* wood, significant variations were observed for diameter and bark per cent. The values for diameter and bark per cent ranged between 14.43 cm (90%) to 20.66 cm (base) and 1.76 per cent (90%) to 2.35 per cent (base), respectively.

5.2 PHYSICAL PROPERTIES

Analysis of vertical variation showed that except fiber length and vessel diameter in different bole heights of *Melia dubia*, all other parameters showed significant vertical variation. At different bole heights of *Melia* wood, maximum moisture content (75.34%) was observed at 90 per cent of total bole height, whereas maximum specific gravity (0.403), fiber diameter (0.0263 mm) and vessel frequency (9.671/mm^2) were noticed at base.

5.3 CHEMICAL PROPERTIES

Among all the different chemical parameters, significant variation was found along the total bole height of the tree. The maximum value for cold water-soluble extractives was obtained at the base (5.71%) and minimum value was noticed at 90 per cent (3.83%) of total bole height. The values for hot water-soluble extractives ranged between 8.56 per cent (base) to 6.20 per cent (90%). For alcohol-benzene soluble extractives observed values ranged between 10.10 per cent (base) to 8.01 per cent (90%). The holocellulose content, lignin content and ash content values ranged between 68.40 per cent (base) to 71.26 per cent (90%), 26.66 per cent (base) to 25.08 per cent (90%) and 1.88 per cent (base) to 2.63 per cent (90%), respectively.

5.4 MECHANICAL PROPERTIES

Analysis of variation in mechanical properties showed that except bending strength and bending modulus of rupture all other parameters showed significant vertical variation The maximum tensile strength (0.072 kN/mm^2), compression strength parallel to grain (0.039 kN/mm^2), compression strength perpendicular to grain (0.039 kN/mm^2) and modulus of elasticity in compression parallel to grain (0.625 MPa) were observed at base. The modulus of elasticity in bending strength (9.327 MPa) and modulus of elasticity in compression perpendicular to the grain (0.078 MPa) were noticed at 90 per cent of total bole height of the tree.

CONCLUSIONS

The following conclusions could be inferred from present study:

- The diameter and bark percentage of the tree decreased with increase in the bole height of the tree.
- The moisture content and maximum moisture content showed increasing trend along the bole height of tree, while the specific gravity, fiber diameter and vessel frequency showed decreasing trend along the bole height of tree.
- A decreasing pattern along the bole height from base to top of tree was observed in hot water-soluble extractives, cold water-soluble extractives, alcohol benzene soluble extractives and lignin content, while an increasing trend along the bole height has been observed in holocellulose content and ash content.

- The tensile strength, compression strength parallel to grain and Compression strength perpendicular to grain were found maximum at the base and minimum at 90 per cent of total bole height.

- The tensile modulus of elasticity was found highest at 30 per cent and lowest at 60 per cent, whereas the bending modulus of elasticity was highest at 45 per cent and lowest at 90 per cent of total bole height.

- The modulus of elasticity in compression strength parallel to grain was maximum at base and minimum was at 60 per cent of total bole height, while the modulus of elasticity in compression strength perpendicular to grain was recorded maximum at 90 per cent and minimum at 30 per cent of total bole height.

On the basis of present study on vertical variation in *Melia dubia*, mechanical properties were showing increasing trend from base up to 30 per cent of total bole height makes it useful for construction purpose, whereas maximum holocellulose content present at 45 – 90 per cent of bole height make the wood suitable for pulp, paper and plywood making.

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APPENDIX- I

1. Analysis of variance for diameter of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	101.228	16.871	49.016
Error	14	4.819	0.344	
Total	20	106.047		

2. Analysis of variance for bark percentage of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.604	0.101	14.646
Error	7	0.048	0.007	
Total	13	0.652		

3. Analysis of variance for moisture content of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	338.271	56.378	18.375
Error	14	42.956	3.068	
Total	20	381.227		

4. Analysis of variance for maximum moisture content of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	4,218.745	703.124	20.168
Error	14	488.088	34.863	
Total	20	4,706.834		

5. Analysis of variance for specific gravity of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.008	0.001	19.521
Error	14	0.001	0.000	
Total	20	0.009		

6. Analysis of variance for fibre length of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.007	0.001	0.529
Error	14	0.031	0.002	
Total	20	0.038		

7. Analysis of variance for fibre diameter of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.000	0.000	4.092
Error	14	0.000	0.000	
Total	20	0.000		

8. Analysis of variance for vessel diameter of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.001	0.000	2.754
Error	14	0.000	0.000	
Total	20	0.001		

9. Analysis of variance for number of vessels of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	1.647	0.275	5.595
Error	14	0.687	0.049	
Total	20	2.335		

10. Analysis of variance for cold water soluble extractives of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	8.695	1.449	62.663
Error	14	0.324	0.023	
Total	20	9.019		

11. Analysis of variance for hot water soluble extractives of *Melia dubia*

Source of Variation	DF	Sum of Square	Mean Squares	F-Calculated
Treatment	6	16.452	2.742	113.944
Error	14	0.337	0.024	
Total	20	16.789		

12. Analysis of variance for alcohol-benzene soluble extractives of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	11.414	1.902	29.709
Error	14	0.896	0.064	
Total	20	12.311		

13. Analysis of variance for holocellulose content of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	19.066	3.178	7.872
Error	14	5.651	0.404	
Total	20	24.718		

14. Analysis of variance for lignin content of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	8.306	1.384	3.672
Error	14	5.278	0.377	
Total	20	13.584		

15. Analysis of variance for ash content of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	1.597	0.266	32.887
Error	14	0.113	0.008	
Total	20	1.711		

16. Analysis of variance for tensile strength of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.002	0.000	3.730
Error	14	0.001	0.000	
Total	20	0.004		

17. Analysis of variance for bending strength of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.000	0.000	1.333
Error	14	0.000	0.000	
Total	20	0.000		

18. Analysis of variance for compression strength parallel to grain of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.000	0.000	13.519
Error	14	0.000	0.000	
Total	20	0.000		

19. Analysis of variance for compression strength perpendicular to grain of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.002	0.000	4.865
Error	14	0.001	0.000	
Total	20	0.003		

20. Analysis of variance for bending modulus of rupture of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.000	0.000	1.432
Error	14	0.001	0.000	
Total	20	0.001		

21. Analysis of variance for modulus of elasticity in tensile strength of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	1.721	0.287	6.658
Error	14	0.603	0.043	
Total	20	2.324		

22. Analysis of variance for modulus of elasticity in bending strength of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	11.349	1.891	7.246
Error	14	3.655	0.261	
Total	20	15.004		

23. Analysis of variance for modulus of elasticity in compression strength parallel to grain of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.141	0.023	5.014
Error	14	0.066	0.005	
Total	20	0.206		

24. Analysis of variance for modulus of elasticity in compression strength perpendicular to grain of *Melia dubia*

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Treatment	6	0.004	0.001	3.677
Error	14	0.003	0.000	
Total	20	0.006		

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Title of Thesis	**:**	**Vertical variation in physico-chemical and mechanical properties of *Melia dubia* Cav.**
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Total Pages of the thesis	**:**	69+iii
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ABSTRACT

The present research entitled **"Vertical variation in physico-chemical and mechanical properties of *Melia dubia* Cav."** was carried out in the Laboratory and Wood Workshop in the Department of Forest Products, College of Forestry, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP) during 2019-20 and 2020-21. *Melia dubia* tree of age about three year was felled and converted into seven logs (base 0%, 15%, 30%, 45%, 60%, 75% and 90%) of total bole height to investigate the physical, chemical and strength properties of the wood. It showed significant variation along the bole height. The values of diameter, bark percentage ranged between 20.66 cm (base) to 14.43 cm (90%) and 2.35 per cent (base) to 7.72 per cent (base), respectively. The moisture content and maximum moisture content (143.61%) were also ranged between 62.79 per cent (base) to 75.34 per cent (90%) and 182.85 per cent (base) to 229.31 per cent (90%), respectively. Maximum specific gravity (0.403) was recorded at base, whereas minimum (0.339) was recorded at 90 per cent. The values for fibre length, fibre diameter, vessel diameter and number of vessels ranged between 1.007 mm (base) to 0.947 mm (90%), 0.0263 mm (base) to 0.0227 mm (90%), 0.231 mm (base) to 0.218 mm (90%) and 9.671/mm^2 to 8.864/mm^2, respectively. The cold water-soluble extractives, hot water-soluble extractives, alcohol-benzene soluble extractives, holocellulose content, lignin content and ash content ranged between 5.71 per cent (base) to 3.83 per cent (90%), 8.56 per cent (base) to 6.20 per cent (90%), 10.10 per cent (base) to 8.01 per cent (90%), 68.40 per cent (base) to 71.26 per cent (90%), 26.66 per cent (base) to 25.08 per cent (90%) and 1.88 per cent (base) to 2.63 per cent (90%) of total bole height, respectively. The tensile strength, bending strength, compressive strength parallel to grain, compression strength perpendicular to grain was ranged between 0.072 kN/mm^2 (base) to 0.039 kN/mm^2 (90%), 0.009 kN/mm^2 (base) to 0.008 kN/mm^2 (90%), 0.039 kN/mm^2 (base) to 0.033 kN/mm^2 (90%), 0.039 kN/mm^2 (base) to 0.012 kN/mm^2 (90%). The maximum value for bending modulus of rupture, modulus elasticity in tensile strength, modulus of elasticity in bending strength, modulus of elasticity compression parallel to grain, modulus of elasticity compression perpendicular to grain were 0.182 kN/mm^2 (30%), 1.423 kN/mm^2 (30%), 9.327 kN/mm^2 (90%), 0.625 kN/mm^2 (base) and 0.078 kN/mm^2 (90%), respectively.

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Whether sponsored by some state/ Central Govt./Univ./SAARC	:	NA
Scholarship/ Stipend/ Fellowship, any other financial assistance received during the study period	:	University Merit Scholarship

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