WOOD PROPERTY VARIATION IN JACK TREES (*Artocarpus heterophyllus* Lam.) GROWN IN THRISSUR DISTRICT, KERALA

By

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2020

DECLARATION

I, hereby declare that this thesis entitled "**WOOD PROPERTY VARIATION IN JACK TREES (*Artocarpus heterophyllus* Lam.) GROWN IN THRISSUR DISTRICT KERALA"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associate ship, fellowship or other similar title, of any other University or Society.

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Place: Vellanikkara, Thrissur
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LIST OF ABBREVIATIONS

%	:	percentage
µm	:	micrometer
Dr.	:	Doctor
%	:	Percentage
µm	:	Micrometer
kg	:	Kilogram
g	:	Gram
m	:	Meter
cm	:	Centimetre
mm	:	Millimetre
^{0}C	:	Degree celsius
et al.,	:	And others
etc.	:	Et cetera
pp.	:	Pages
SPSS	:	Statistical Package for Social Sciences
ANOVA	:	Analysis of Variance
CIE	:	International Commission on Illumination
MC	:	Moisture content
VS	:	Volumetric shrinkage
GSG	:	Green Specific gravity
OSG	:	Oven dry specific gravity
TS	:	Tangential shrinkage
RS	:	Radial shrinkage
CWS	:	Cold water-soluble extractives
HWS	:	Hot water-soluble extractives
ALBZ	:	Alcohol benzene extractives
LGN	:	Klason lignin content
HCE	:	Holocellulose content
CLE	:	Cellulose content

HCLE	:	Hemicellulose content
NaOH	:	Sodium hydroxide
FL	:	Fibre length
FD	:	Fibre diameter
VD	:	Vessel diameter
VA	:	Vessel area
VL	:	Vessel length
VF	:	Vessel frequency
RW	:	Ray width
RH	:	Ray height
RF	:	Ray frequency
HS at LP	:	Horizontal Stress at Limit of Proportionality
MOR	:	Modulus of Rupture or Rupture modulus
MOE	:	Modulus of Elasticity or Elastic modulus
HS at ML	:	Horizontal Stress at Maximum Load
CSPR at ML	:	Compression perpendicular to grain at Maximum Load
FS at LP	:	Fibre Stress at Limit of Proportionality
MOEB	:	Modulus of Elasticity Bending
TS at ML	:	Tensile Strength at Maximum Load
CSPL at LP	:	Compression parallel to grain at Limit of Proportionality
CSPL at ML	:	Compression parallel to grain at Maximum Load
MOE CSLP	:	Modulus of Elasticity Compression parallel to grain
MOE CSPR	:	Modulus of Elasticity Compression perpendicular to grain
CSPR at LP	:	Compression perpendicular to grain at Limit of Proportionality

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1. INTRODUCTION

The unique characteristics and relative abundance of wood have made it a natural material for homes and other structures, furniture, tools, vehicles and decorative objects from time immemorial. Today, for the same reasons, wood is valued for its various purposes (Rowell, 2013). Wood quality can be elucidated as the suitability for a particular end use which shows the wood properties that individually or in combination, have a beneficial effect on a specific wood product (Barnett and Jeronimidis, 2003). The significance of wood quality has been recognized throughout the history, as native people globally understood the unique parameters of different tree species and used a particular species best suited for certain applications. Studies on these wood parameters expand the knowledge base for promoting proper wood utilization which in turn will help to boost the consumer for proper usage of the timber. Though scientific data on the natural durability, anatomical characteristics, chemical behavior, and mechanical parameters are accessible for many commercial species, more reliable knowledge on wood variation are crucial for engineers, architects, and carpenters in order to use timber more efficiently. As the anatomical studies on wood are important in finding out its influence on strength parameters, appearance, resistance to preservative treatment and decay. The study of chemical nature of wood is of considerable value in discovering the utilization of wood as potential raw material for manufacture of pulp and paper, carbonization, bioethanol etc.

Artocarpus heterophyllus Lam. belonging to the family Moraceae and widely known as Jackfruit tree or Ceylon Jack tree, is one of the major and commonly observed trees in the homegardens of certain parts of India and Bangladesh (Bose, 1985; Elevitch and Manner, 2006). In India, the trees are noticed to be distributed continuously as it occurs in the moist evergreen forests, places where rainfall is more and, sporadically in areas where it is less (Singh *et al*., 1963; Narasimham, 1990; Muralidharan *et al*., 1997). The place of origin of Jack wood is unknown, however it is believed to be indigenous to the rainforests of the Western Ghats upto an elevation of about 1200 m (Luna, 2005). It is a medium sized to large evergreen tree with short trunk and large crown (Das and Alam, 2001). The mature tree attains a height of 8 m–25 m and a stem diameter of 30 cm–80 cm. The linear cylindrical stem is usually covered with rough bark which exudes milky latex. The heartwood is yellow when freshly cut but gradually turns light brown on exposure, with a specific gravity of 0.6-0.7 (Manjunath, 1948). The canopy shape is usually conical or pyramidal in young trees and becomes spreading and domed in older trees. It is monoecious and both male and female inflorescences are found on the same tree (Bose, 1985; Morton, 1987).

It is categorized as medium hardwood and is resistant to termite attack, fungal and bacterial decay and is easy to season. When compared to teak wood, *Artocarpus heterophyllus* wood is considered superior in many aspects *i.e.* takes fine polish beautifully, used for furniture, construction, turnery and inlay work, masts, oars, implements and musical instruments because of its availability. The heartwood is used for carving, musical instruments such as drums, veena etc and almost all household, ship building and other industrial purposes (Watt, 1972). The wood is extensively used in India and Sri Lanka and is even exported to Europe. Roots are greatly prized for carvings and picture framing (Orwa *et al*., 2009). The heartwood yields a dye which is used in Burma for dyeing of robes of priests. Due to the fragmented households and pressure over land, there is a growing interest for planting dwarf varieties over tall varieties in the recent years. Being such a wood species with versatile and manifold uses there is a pertinent need to increase the planting of tall varieties of Jack trees. Due to global timber crisis it is worthwhile to explore further utilities of Jack wood.

The wood properties are important factors that influence the workability of any material. The key features in the utilization of wood for different applications are physical properties of wood which are related to the various physical states of wood such as colour, density, weight, reaction of the wood to sound, heat, light etc. These parameters of the wood can vary from site to site, within site, among different and same species. Microscopic feature of taxonomic significance or of importance in the selection of wood for a particular application include texture, colour and lusture. The sapwood and heartwood pattern is one of the most obvious feature that can be observed on the cross or radial section of mature tree trunk. More precise criterion for heartwood determination is the absence of living cells within the zone, and in particular, cells of ray parenchyma which remains alive for longer than the neighbouring prosenchymatous elements (Wyssling and Bosshard, 1959). The patterns of parenchyma arrangement are helpful in description of wood anatomy and in the identification of wood species. Kribs (1959) implies different categories of vessel arrangement in describing the anatomy of hardwood in his key-sort system *viz.,* pores evenly distributed, pores in echelon, pores and pore group in radial lines, pores solitary, pores and pore group in straight to wavy tangential bands and pores in radial flame like cluster.

According to Panshin and Zeeuw (1980), the principal chemical constituents of wood are cellulose, hemicellulose, lignin and minor substances called extractives. Wood is primarily consituted of cellulose, hemicelluloses, lignin and extractives. All these components contribute to fibre properties, which results the influence on wood properties. The two paramount chemical components in wood, lignin (18-35%) and carbohydrate (65-75%) are complex, polymeric materials along with minor amount of extraneous materials, mostly in the form of organic extractives and inorganic material (ash). Overall, wood has a fundamental composition of about 50 per cent carbon, 6 per cent hydrogen, 44 per cent oxygen, and trace amounts of several metal ions.

Cellulose is the major chemical components of woody cell wall and contributing 40-50 per cent of the woods dry weight. Unlike cellulose, hemicelluloses are much lower in molecular weight compared to cellulose. They are closely connected with cellulose and appear to contribute as a structural component in the tree. Lignin comprises 15 to 35% of polymeric substances and often called the cementing agent which binds individual cells together. Extractives are a variety of organic compounds including fats, waxes, alkaloids, simple and complex phenolics, gums, resins, starches terpenes and essential oils. The amount of extractives in wood varies from less than 3 to over 30 per cent of the wood on oven dry weight (Bowyer *et al*., 2003)

Wood is highly anisotropic in its properties *i.e.* it has distinct properties in different planes and this is on account of its cellular structure and physical arrangement of the cellulose chain molecules within the cell walls (Schniewind, 1989). It is a natural, renewable cellular resource of botanical origin with unique structural and chemical characteristics that render its desirable end uses for variety of purposes with outstanding strength-to-weight properties (Hingston *et al*., 2001). The material's resistance to load is related to mechanical properties of the wood which includes resistance to external stresses such as tension, compression, bending, shear and also cleavage (Araujo, 2007). Proficiency about the strength properties of different species of wood comprises the basis of economic application in all kind of uses the wood is to be put and the techniques by which wood can be utilized is considerably influenced by the strength properties exerted by timber (Rowell, 2013).

At present, not much work has been done on the wood parameters of *Artocarpus heterophyllus* wood. The studies on wood properties and their interrelationships helps in fostering proper wood utilization and also promotes the further tree improvement programmes to develop quality Jack trees thereby not relegating the tall varieties by only taking into account the tree as a source of fruit production. Therefore, the present study has been proposed to find variation in wood properties of *Artocarpus heterophyllus* wood between different altitudinal zones (Lowland, Midland and Highland) and girth classes within these altitudinal zones of Thrissur district, Kerala with the following objectives:

- To study variation in physical properties of jack wood
- To study variation in anatomical properties of jack wood
- To study variation in chemical properties of jack wood
- To study variation in mechanical properties of jack wood

2. REVIEW OF LITERATURE

The wood properties are important factors that influence the workability of wood. Variations in wood properties are natural due to its orthotropic nature and these properties even vary in the same tree. This examination is an undertaking to give information, at each conceivable chance, on the nature and size of changeability in different wood properties of jack tree wood assembled from different market sites. The literature pertaining to the present work *i.e.*, **"Wood property variation of jack trees (*Artocarpus heterophyllus* Lam.) grown in Thrissur district, Kerala"** have been reviewed and discussed under the following headings:

2.1 Physical properties of wood
2.2 Anatomical properties of wood
2.3 Chemical properties of wood
2.4 Mechanical properties of wood

2.1 PHYSICAL PROPERTIES OF WOOD

The versatility of wood is demonstrated by a wide variety of products, which is a result of spectrum of desirable physical characteristics among the various species of wood. The utilization of wood for different applications are mainly depend on physical characteristics which includes colour, density, weight, reaction of the wood to sound, heat and light. Those charcteristics which appear under the influence of external mechanical or chemical factors on the wood do not include physical characteristics. The versatility of wood is demonstrated by a wide variety of products, which is a result of spectrum of desirable physical characteristics among the various species of wood. These characteristics of the wood can vary from site to site, within site and also among different and same species.

Smith (1954) studied the maximum moisture content for determining specific gravity of small wood samples. The minimal longitudinal shrinkage produced and increased radial as well as tangential shrinkage was from the dense wood resulted from fibre with thick walls and a low microfibril angle (Dadswell, 1958). Kennedy and Smith (1959) reported that, the specific gravity increased from 0.33 to 0.38, respectively in *Populus terichocarpa* was due to the change in site from good to poor.

An important parameter to determine wood quality is specific gravity is (Elliott, 1970: Panshin and Dezeeuw, 1970 and Horn, 1974). Hiller *et al*. (1972) reported that in case heartwood of walnut, the value of specific gravity of walnut averaged 5 per cent greater than the wood. The accumulation of polyphenoles and other extractives in heartwood resulted in higher specific gravity of heartwood was due which were normally not found in sapwood. Kadambi (1972) studied that there was no effect on strength characteristics of teak in India and Myanmar by moderate and heavy thinning. Manwiller (1979) had examined that specific gravity remained relatively stable or decreased slightly with sampling height in twenty-two small diameter hardwood species. Taylor (1979) could not find any relationship in six of eight southern United State hardwood species between sampling height and specific gravity.

Wood density had considerable influence on strength, machinability, conversion, acoustic characteristics, wearability, paper yield etc (Bamber and Burley, 1983). Sanwo (1986) observed that on specific gravity and strength characteristics of teak plantation grown in Nigeria, the rate of growth had no significant influence. Morales (1987) studied 220 species from two tropical forests in Mexico on their wood specific gravity of which half of them were from a tropical rainforest and half of them were from a tropical deciduous forest. The two groups were compared using ‘t-test’. Highly significant differences were found in specific gravity between the species from two areas. The specific gravity of the wood between species within each region and between two regions showed considerable differences. The trees from the drier region showed a higher average density (average 0.78) than that of trees from the more humid region (average 0.58).

Zobel and Buijtenen (1989) had observed that wood density can vary among geographical regions and is highly variable among trees and within individual trees of a given provenance. Compared to slow growing northerly geographical regions, the southerly Sitka spruce geographical regions produced faster growing denser timber. Pipatwattanakul (1989) examined provenance variation in wood density of 6-year-old *Acacia mangium* trial plantation and found value 0.3-0.4 for the wood specific gravity and no significant difference was found among the 16 geographical regions. However, values obtained at the generally drier sites (0.6) were substantially higher than those at wetter sites (0.4) (Awang and Taylor, 1993).

Bhat *et al*. (1990) studied wood density and fibre length of four different age groups *Eucalyptus grandis* plantation grown in Kerala. The average density value varied from 420 to 497 kg m^{-3} among the ages. When compared to the more age group trees, it was observed that density was lowest in the initial growth trees. Taylor (1973) observed that before the gradual rise towards the bark it is common for the density curve to decrease initially in *E. grandis*. Bhat *et al*. (1990) found that there was an increase by 42% of average fibre length from 0.81 mm to 1.15 mm and concluded that age was a very important source of variation in fibre length, thus each age group was significantly different from the other. But later it was contradicted as fibre length in older trees and adult wood is not considerably greater than in young trees. Chapola and Ngulube (1990) from nine sites reported the basic density of 5-8 years old tree species of *Eucalyptus spp*., *Albizzia lebbek, Cassia siamea, Gmelina arbobera* and *Melia azedarach* suitable for particular end uses and found that density varied significantly between species ranging from 300 to 700 kg/m^3. Sharma and Venkaiah (1992) studied twenty-seven hardwood species to evaluate their utility as packing material based on their specific gravity from different agroclimatic zones of Himachal Pradesh. They also found that *Acacia mollissima, Albizzia chinensis, Alnus nitida, Eucalyptus* hybrid, *Grewia optiva, Melia azedarach, Morus serrata* and *Myrica esculenta* have high specific gravity and ranging from of 0.551 to 0.600.

Lim *et al*. (1993) reported wood specific gravity of 4-5-year-old *Acacia mangium* trees and observed that specific gravity was found to increase in the radial direction from the centre to the outer region near the bark. They also reported utilization potential of juvenile wood reduced by its low specific gravity. They also studied the variation in wood density and other wood characteristics within and between trees as well as between three geographical regions of 8- year old *Acacia mangium.* Hedge *et al*. (1998) studied the evergreen and semi-evergreen rain forests of Western Ghats in India, relation between bark thickness and girth in a large sample of trees. They reported that there was a significant tendency for bark thickness to increase with tree girth. Varghese *et al.* (2000) examined growth, wood characteristics and bark thickness in relation to climatic, edaphic and latitudinal factors in seven plantations as well as two natural populations of 60-year-old teak from different ecotypes in Peninsular India. They have reported that for very moist and moist populations, sapwood content in teak population was negatively correlated with growth rate with significantly lower values. In contrary bark thickness was higher for the very moist populations which showed a positive correlation with tree girth. Further, wood density and sapwood content showed significant negative co-relation. Wagenfuhr (1996) recorded that at 12-15 per cent moisture content, average the density of *Betula pendula* wood was 630 kg/m^3.

Chauhan *et al.* (2001) studied variation in specific gravity and wood anatomy from experimental plantations in Uttarakhand, India in 18 clones of 10-year-old *Populus deltoides* trees. They found that specific gravity was maximum at 50 per cent tree height and fibre length at 25 per cent of tree height and showed upward decreased trend with respect to growth. At breast height fibre length and specific gravity increased rapidly up to the 6^{th} year followed by a slower rate of increase up to the 8^{th} year. Breast height values of specific gravity and fibre length were highly correlated with whole tree values for these two parameters. However, Mitchell and Denne (1997) and Simpson and Denne (1997) had found that for comparable ring numbers, wood density was slightly greater at breast height as compared to height above dbh in the tree.

Luxmi *et al*. (2001) studied 10 years old trees of 18 clones of *Populus deltoides* collected from experimental plantations in Uttarakhand, India on their variation in specific gravity and wood anatomy. The specific gravity reached maximum at 50 per cent tree height and fibre length at 25 per cent of tree height, thereby showing an upward decreased trend with growth. Fibre length and specific gravity increased rapidly upto the 6^{th} year at breast height followed by tendency to level off by a slower rate of increase up to the 8^{th} year. Breast height values of specific gravity and fibre length were highly correlated with whole tree values for these two parameters. Verma *et al.* (2001) studied 10-year-old plants growing in a field trial laid out at New Forest Campus, Dehradun, Uttarakhand, India. They reported the variations observed in the specific gravity of wood in segregating populations of F_2 and F_3 hybrids of *Eucalyptus citriodora* and *E. torelliana.* A comparison of specific gravities of wood was made with parent species involved in hybridization. The range for F_2 and F_3 recombinants in specific gravity of wood observed was 0.81-0.89 in *E. citriodora,* 0.63-0.66 in *E. torelliana* and 0.52-0.67.

Cordero and Kanninen (2003) evaluated seventeen plants were selected from 11 sites of different climatic conditions to study heartwood, sapwood, bark content and wood density in young and mature teak trees. The highest heart wood proportion of stem volume (over bark) was ranged between 0.4 to 61% whereas, sap wood proportion ranged from 24 and 72 %. While bark represented for 14-37 % of the total volume. Heartwood proportion was significantly different ($p<0.05$). Among different climatic zones: 'wet' sites produced less heartwood than 'dry' sites. Stem diameter (under bark) and heartwood diameter at different stem height differed among samples trees, even when plotted in relative values to avoid dependency which stem size.

Nicholls *et al.* (2003) reported that sample moisture content ranged from 31.4 per cent to 149.7 per cent (on the basis of oven-dry weight), with a standard deviation of 30.6 per cent in western hemlock (*Tsuga heterophylla*) wood in Alaska. Average moisture content at a given height ranged from about 70 to 85 per cent and there was no significant moisture variation among sample heights. A moisture content of 50 per cent was not uncommon for pith-centered samples, whereas most samples more than 5 inches from the pith has 100 per cent moisture content. There was considerable variation in overall moisture content among trees, ranging from about 69 to more than 85 per cent. Moisture content variation among butt logs was also considerable, ranging from about 58 to 95 per cent.

Tharakan *et al*. (2003) reported that via thermo-chemical and bio-chemical processes, the woody biomass feedstock produced from willow and hybrid poplar can be converted in to bioenergy. They observed a lesser amount of variation for specific gravity (0.33-0.48) and moisture content (49-56 per cent). Willow clones had higher specific gravity and bark percentage than hybrid poplar clones. Zuo and Zhong (2003) revealed that among poplar clones, wood density showed significant variation and they also revealed significant difference in wood basic density among the growth rings, which showed an increased tendency along the direction from the pith to bark. With increasing tree height, the mean wood basic density showed increasing trend. They also reported significant variations in fibre diameter and the ratio of fibre length to diameter among poplar clones. There were significant differences in fibre length and fibre diameter among the growth rings, which had an increasing tendency along the direction from pith to bark. With an increase in height of the trees, the fibre length and fibre diameter showed declining trend.

Hannrup *et al*. (2004) studied two 19-yr-old clonal trials and a 40-yr-old full-sib progeny trial of Norway spruce (*Picea abies)* for determining the genetic parameters for wood and growth traits. High broad-sense heritability of 0.4 were found for wood density traits, lignin content, number of internal cracks, growth traits, spiral grain and number of resin canals in the clonal trials. Santos *et al.* (2004) reported the basic density of 536 kg/m^3 and 527 kg/cm^3 for the two wood samples of *Eucalyptus globulus viz.*, industrial chip sample and clone tree respectively. Oliveira *et al.* (2005) reported that for *Eucalyptus* species, the specific gravity generally increased in the direction of pith to bark. Kumar *et al.* (2005) observed significant variation in height and diameter of candidate plus trees of *Dalbergia sissoo* Roxb. They also observed that the mean height ranged from 15.00 m to 43.00 m and mean diameter ranged from 17.30 cm to 116.50 cm.

Kumar and Sharma (2005) observed significant positive correlation between bark per centage of candidate plus trees and sapwood percentage of *Dalbergia sissoo* Roxb. with correlation coefficient of 0.609. With a correlation coefficient of 0.324, they also observed significant positive correlation between bark percentage and specific gravity. Monteoliva *et al.* (2005) studied six 13-year-old willow clones growing under two different site conditions in Argentina and their variability of wood basic density and fibre length. They observed that basic density ranged from 0.364 to 0.455 kg/m^3site influence was significant for, which. Clones '*americano*' and hybrid *cv.* '*A 13-44*' showed the highest density values in both sites. However, the fibre length, values of the continental site were significantly higher for each clone and mean values varied between 837.1 μm and 1142.1 μm. Heritability values showed that the genetic control was for fibre length ($h^2 = 0.32$) lesser than for density ($h^2 = 0.65$).

Pande and Singh (2005) reported that specific gravity ranged from 0.531 to 0.596 for *Dalbergia sissoo* clones from different locations of Dehradun. They also observed that sites have a significant effect in variation of specific gravity due to environmental impact on wood quality and is more than the inherent nature of clone. Sharma and Sharma (2005) observed high density *Robinia pseudoacacia* trees managed under short rotation system and found significant decrease in the wood density from base to top. The bark per cent showed a reverse trend while wood percentage increased from base to top and the planting densities also showed variation in wood and bark percentage. Similarly, Nimkar and Sharma (2006) observed in *Pinus roxburghii* a significant variation in bark thickness and specific gravity for high resin yielders. The maximum bark of 9.54 per cent was recorded in UHF-check and minimum of 3.39 per cent in Gandhir HRY. The highest and lowest specific gravity of wood was recorded in Bumbloo-check (0.66) and UHF-4 HRY (0.54) respectively.

Shanavas and Kumar (2006) observed the wood characteristics of three locally important fast-growing tree species occurring scattered and also as boundary planted trees on the agricultural lands of Kerala (*Acacia auriculiformis, Acacia mangium,* and *Grevillea robusta)*. Basic wood density of *A. auriculiformis* was greater than that of *A. mangium* and *G. robusta,* while moisture content followed a reverse sequence: *G. robusta*>*A. mangium*>*A. auriculiformis*. Wood density also increased from inner to outer positions along the radial direction, except for *G. robusta*. Although moisture content decreased from the inner to outer position of the specimens for *A. mangium,* no predictable pattern was discernible in this respect for the other two species. Chen (2006) also studied variation of wood basic density for four *Eucalyptus* clones in Stora Enso Guangxi (China) plantation ranged from 452.84 kg/m^3 to 517.59 kg/m^3. The mean basic density of the four species (*Antiaris toxicaria, Celtis mildbraedii, Alstonia boonei and Maesopsis eminii*) ranged between 325 kg/m^3 and 630 kg/m^3. *Celtis mildbraedii* had the highest basic density i.e. 630.16 kg/m^{3}and *Alstonis boonei* the lowest *i.e*. 361.81 kg/m^3 (Ziwa *et al.,* 2006).

Sharma *et al.* (2006) studied seven-year-old plantation of *Simarouba glauca* for wood variation in shrinkage (radial, tangential, volumetric and longitudinal) and specific gravity with moisture content. The results revealed that the standard specific gravity increased with decreasing moisture content. Low value of specific gravity suggests that the timber is light and useful for making toys and other handicraft items by artisans. Zziwa *et al.* (2006) reported the mean basic density of the four species (*Antiaris toxicaria, Celtis mildbraedii, Alstonia boonei and Maesopsis eminii*) ranged between 325 kg/m^3 to 630 kg/m^3. Among all, *Celtis mildbraedii* had the highest basic density *i.e.* 630.16 kg/m^3 and *Alstonis boonei* the lowest *i.e.* 361.81 kg/m^3. Basic density and strength characteristics decrease moderately from the pith to the centre of radius then increased to the bark. Chen (2006) had also studied variation of wood basic density for four *Eucalyptus* clones in Stora Enso Guangxi (China) plantation where basic density ranged from 452.84 kg/m^3 to 517.59 kg/m^3.

Dhillon and Sidhu (2007) collected wood samples of Poplars clones from two locations of Punjab viz. central plain region (Ludhiana) and semi-arid region (Bathinda) and measured specific gravity (at d.b.h.). Specific gravity showed significant differences among both the locations with ranged from 0.403 to 0.475 in central plain region and from 0.356 to 0.436 in semi-arid region of Bathinda. Guler *et al*. (2007) studied black pine (*Pinus nigra* Arnold) plantations and found that wood densities of 0.464 and 0.431g cm^{-3} for air and oven dry respectively while investigating physical and chemical characteristics of juvenile wood. The radial, tangential and volumetric shrinkage values were 4.05, 6.19 and 10.24%, respectively whereas the swelling in radial, tangential and volumetric were recorded as 3.69, 7.79 and 11.5 %., respectively.

Mani and Parthasarathy (2007) reported the basic wood density of 41 tree species, analysed by oven-dry weight by volume which ranged from 0.47 to 0.89 g cm^{-3} for the coastal sites tropical dry evergreen forests of Peninsular India and 0.46 to 0.92 g cm^{-3} for inland sites. Tang (2007) stated that White ash *(Fraxinus)* wood is a strong and elastic timber used for furniture, tool handles, and sporting goods such as baseball bats. The shrinkage and swelling characteristics of White ash wood were analysed with the use of drying and absorbing moisture methods. The changes in sizes in three dimensions with wood moisture content were preliminarily detected, and were then compared with other three varieties. The results showed that the basic density of the White ash wood as 0.73 g/cm^3.

Agbontalor (2008) observed that specific gravity of wood has not been adequately reported to be a factor directly or indirectly influencing its selection for incorporation into or retention in some of the agroforestry systems. The specific gravity were evaluated and found to range between 0.42 and 0.85 with eleven of the species having values >0.60 of twelve wood species that top the priority ranking of respondents in Akinyele and Ido Local Government Areas (LGAs), Oyo State, Nigeria, where the predominant type of agroforestry system practiced is that of scattered trees in croplands, Lekha and Sharma (2008) found that at the base of tree and at 60 per cent of sampling height, the highest and lowest sapwood moisture content was recorded for *Acacia catechu.* Gurau *et al.* (2008) studied three species *viz*. maple (*Acer* spp.), scots pine (*Pinus sylvestris* L.) and beech (*Fagus sylvatica* L.) and compared the moisture content in branch and stem. They noticed that in beech wood, the moisture content was 15.4 per cent and 33.8 per cent in the stem and branch respectively. While maple tree showed moisture content of 11.8 per cent and 16.9 per cent in stem and branch respectively. In scots pine, the moisture content in stem was 15.3 per cent while 20.9 per cent in the branch. The density (kg/m^3) also revealed similar trend with the values to be 669 kg/m^3 in the stem while, 805 kg/m^3 in the stem of beech wood at 12 per cent moisture content in three wood species. It was found scots pine showed 586 kg/m^3 in the stem and 492 kg/m^3 in the branch while 598 kg/m^3 in the stem and 678 kg/m^3 in the branch of maple tree.

Venson *et al*. (2008) studied physical wood characteristics of *Melia azedarach i.e.* density and dimensional stability. The medium density (0.56-0.68-0.76 g/cm^3 at 12% moisture content) wood when compared with true mahogany (*Swietenia macrophylla*) was found similar and is of moderate dimensional stability. *M. azedarach* wood from planted trees were found suitable for the manufacture of decorative veneers sliced and peeled, furniture parts, plywood, glue board, laminates, paneling, window and door framing, general carpentry, and light construction under cover based on the property profile established by the present study. Martinez *et al.* (2009) observed that wood density was more significantly correlated with precipitation and aridity compared to temperature while studying wood density in shrubs from eight field sites in North and South America. High wood density was achieved through increase in the proportion of wall relative to lumen reductions in cell size. Wood density was independent of vessel traits, suggesting that this trait does not impose conduction limitations in shrubs. Nguyen *et al.* (2009) analysed the growth, specific gravity and wood fibre length of *Acacia mangium, Acacia auriculiformis, Acacia* hybrid clones, and combinations, which were planted in a trial forest in Bavi, Vietnam. Superiority of hybrids over their parents ranged from 3.63-4.16 per cent for diameter, from 6.9- 20.7 per cent for specific gravity and from 6.1-12.8 per cent for wood fibre length. Wood fibre length was initially 0.5-0.6 mm near the pith, increased slowly and finally reached 1.0-1.2 mm near the bark. The specific gravity of *Acacia mangium* increased from 0.49-0.58 near the pith to 0.63-0.47 near the bark. Sungpalee *et al*. (2009) had observed that with respect to elevation, slope convexity, sapling growth rate and sapling mortality stand-level mean wood density was significantly negatively related, and positively related to slope inclination. West-facing slopes had significantly lower stand-level mean wood densities than east-facing slopes They further found that stand-level wood density was lower at higher elevations on eastern slopes than at other locations within the study plot of 15 ha plot in northern Thailand.

Izekor and Modugu (2010) observed the variations of specific gravity and shrinkage characteristics of 23 years old plantation grown Teak (*Tectona grandis*) in Ologbo Forest Reserve. Results revealed that with increase in the tree height specific gravity decreased, while shrinkage characteristics increased with height along the tree bole. There was increase in wood specific gravity from inner wood and decrease from the tree base to the top. The interaction between tree height and its radial positions were not significant at 0.05% probability level. Lokman and Noor (2010) studied 13-year-old provenance trials of *Acacia mangium* established at five sites in Sabal, Jakar, Oya, Labang and Sawai in Sarawak Malaysia and found that radial variation in specific gravity increased from pith to bark, ranging from 0.20 at pith to 0.80 at bark with a mean and coefficient of variation of 0.56 and 17.05 per cent, respectively.

Izekor *et al*. (2010) observed the effect of density on variation in the mechanical characteristics of *Tectona grandis*. Wood density and mechanical characteristics increased with increase in age hence age was the most important source of variations in wood density, MOR, MOE and CS parallel to grain of *Tectona grandis* wood. Whereas wood density and mechanical characteristics increased from pith to bark, they however decreased from base to top at any particular height. Lokman and Noor (2010) studied provenance trials of 13-year-old *Acacia mangium* established at five sites in Sabal, Jakar, Oya, Labang and Sawai in Sarawak, Malaysia. They observed that radial variation in specific gravity increased from 0.20 at pith to 0.80 at bark with a mean and coefficient of variation 0.56 and 17.05 per cent, respectively. Site provenance contributed significantly towards specific gravity in *A. mangium*. Interaction between provenance and site was highly significant which involved a change in provenance ranking across the sites. The variation in radial direction was the largest contributor to the total variance component in specific gravity.

Rokeya *et al.* (2010) observed hybrid *Acacia*, produced from natural crossing between two introduced timber species (*Acacia auriculiformis* and *Acacia mangium*) and studied its physical characteristics. The timber obtained from hybrid *Acacia* was of medium dense having specific gravity 0.56 at green condition which was less than that of teak (*Tectona grandis*). From the study of mechanical characteristics, it was evident that the species was moderately strong and suitable for making furniture and other household articles. Sagheer and Prashad (2010) observed *Dipterocarpus indicus* among different populations in western ghats of Karnataka and studied variation in wood specific gravity, density and moisture content. They noticed that the wood physical characteristics showed significant variation among different populations and were affected by environmental factors.

Izekor and Fuwape (2011) studied *Tectona grandis* wood in Edo State, Nigeria and reported that the mean values of fibre length as 1.45, 1.73 and 1.96 mm; fibre diameter as 26.79, 29.47 and 32.83 µm; fibre lumen width as 18.17, 15.60 and 14.17 µm while the mean values for fibre wall thickness as 5.87, 7.89 and 9.80 µm for 15, 20 and 25 years old respectively. Fibre length, fibre diameter and cell wall thickness increased with increase in age whereas fibre lumen width decreased with increase in age. Kiaei and Samariha (2011) analysed fibre dimensions, physical and mechanical characteristics of five hardwood species. The parameters such as fibre length, fibre width, cell wall thickness and lumen diameter), physical (oven-dry density) and mechanical characteristics (modulus of rupture, Modulus of Elasticity, compression parallel to the grain) were studied. The relationship between mechanical strength traits to that of physical characteristics (wood density) and anatomical characteristics were determined. They reported that the types of plant species had significant effect on the different wood characteristics. They also studied wood physical characteristics of 35-year-old *Ulmus glabra* trees from the Arasbaran-Ardebil site located in northwestern part of Iran. The mean of wood oven-dry density, basic density and volumetric shrinkage were 0.656, 575 kg/m^3 and 12.39 %, respectively.

Naji *et al*. (2011) analysed the wood density relationship and anatomical characteristics between two different clones and planting densities as well as its variations from pith to bark in 9-year-old eight rubber trees (*Hevea brasiliensis*). Wood density of 0.65 and 0.54 g/cm^3 were recorded in clone I and clone II respectively, and planting densities revealed density values from 0.50 and 0.60 g/cm^3. From pith to bark, wood density and fibre features showed an increasing trend while vessel parameters also showed a direct relation with planting density. They found that with longer fibre length and higher wood density, the characteristics of clone II were comparatively better than clone I. Pande (2011) studied 10 clones of *Populus deltoides* raised by WIMCO Plantations Ltd. at Rudrapur (Udhamsingh Nagar), Uttarakhand, India and reported that within ramet variation due to radial location was observed significant for specific gravity showed increased trend from pith to periphery. Variation for the d.b.h. was also significant for the clones. Female parents showed higher specific gravity than the male parents.

Pande and Dhiman (2011) have evaluated 10 clones of *Populus deltoides* Bartr. ex Marsh and studied intra- and inter-clonal variations in the wood elements dimensions and specific gravity. Except vessel element length for intra-clonal variations, inter- and intra-clonal variations were significant for all the wood traits. Within-ramet variations due to radial location were significant for fibre length and specific gravity. Pande and Singh (2005) in contrary however stated these variations were significant due to height of the ramet and non-significant radial and directional variations in specific gravity and fibre length in different clones of *Dalbergia sissoo*. Sheikh *et al*. (2011) observed that the average wood specific gravity was 0.631 and 0.727 for the species at lower and upper elevated regions for hardwood species in Garhwal region. They reported that *Quercus leucotricophora* among the upper elevation species and *Aegle marmelos* among the lower elevation had the highest wood specific gravity and concluded that site has a considerable influence on wood specific gravity. Tavares *et al*. (2011) found that wood and bark fibre length varied between 0.90- 0.96 mm and 1.33- 1.59 mm, respectively when compared wood and bark fibre characteristics of *Acacia melanoxylon* and *Eucalyptus globulus*. The cell wall thickness varied between 3.45- 3.89 µm in wood and 5.02- 5.40 µm in the bark. Wood and bark fibre length decreased from bottom to the top of the tree and the cell wall thickness had no specific pattern for axial variation. Fibre length and cell wall thickness increased from the pith to bark, but the wall thickness increased slightly with some fluctuations.

Dibdiakova and Vadla (2012) conducted a study and results revealed that bark thickness differed between the sites within decreasing pattern along the stem for 2 site locations in Nordland–1 stand of Sitka spruce in Steigen area, and 1 stand of Sitka spruce, 1 stand of Norway spruce, and 1 stand of Lutz spruce in Somna area. Significant differences of bark density between sites, tree species and tree height levels with decreasing trend towards the top were found. Branch density had about 15-20% higher density than wood density and decreased along the crown level. Wood density varied significantly with sites and height of tree-highest pattern on the tree base, decreasing to 20 % of height, and again increasing to the top. The moisture content of branches, wood and bark increased from the base of tree to the top and bark moisture was about 20-25% higher as wood moisture content.

Hossain and Awal (2012) carried out an investigation on some commercially timber species used in Bangladesh to study physical characteristics *i.e.* strength and durability. Seven timber species namely; Teak (*Tectona grandis*), Sal (*Shorea robusta*), Sil Korai (*Albizia procera*), Rain Tree (*Samanea saman*), Jam (*Syzygium *spp.*), Jackfruit (*Artocarpus heterophyllus*), and Mango (*Mangifera indica*) were tested for density, specific gravity, compressive, tensile and bending strength following ASTM standards. The test results revealed that Sal and Teak showed the best performance in tension while for using as compression member Sal, Teak and Jam were the best species. Sal, Sil Korai, Teak and Jam have been found suitable in static bending. Overall, Sil Korai has been found to be the most vulnerable one and the rain tree (*Samanea saman*) showed excellent performance in all chemical environments having minimum loss of strength to the same environments among all the timber species.

Kiaei *et al.* (2012) studied the anatomical, physical and mechanical characteristics of Eldar pine from Marzanbad region, Iran and they noticed that the basic density, oven-dry density, fibre length and cell wall thickness of the wood increased along the radial axis from pith to bark and the wood density also had a strong correlation with volumetric shrinkage. The average density at 12% moisture content was observed to be 578.35 kg/m^3. Pande *et al*. (2012) at Rudrapur (Udhamsingh Nagar), India studied 10 clones of *Populus deltoids* Bartr. ex Marsh. raised by WIMCO Plantations Ltd. They also reported that specific gravity increased with height and also from pith to periphery for the clones. Female parents showed higher specific gravity than the male parents.

Vergas *et al*. (2012) studied the physical and mechanical wood characteristics and found that there were differences in the physical and mechanical characteristics of *Salix viminalis, S. rubens, S. purpurea* and *Salix* species cultivated in the Canoas River Valley, in the Serra Catarinense region of the State of Santa Catarina, Brazil. *Salix viminalis* and *S. purpurea* were similar in density, Modulus of Elasticity whereas higher values of tensile and Modulus of Elasticity was reported in *Salix rubens* and *Salix* species. Wahab *et al.* (2012) reported the physical, anatomical and strength characteristics of three years old cultivated tropical bamboo, *Gigantochloa scortechinii* and found that moisture content at the outer layer was 49.87 per cent, in middle layer 83.82 per cent and for the inner layer was 125.90 per cent. The moisture content was found to be lower at the outer portion and it increased toward the inner portions. The basic density for outer layer, middle layer and inner layer was 0.95

g/cm^3, 0.73 g/cm^3 and 0.58 g/cm^3 respectively. The differences of basic densities at both the nodes and internodes were due to the fibre wall thickness.

Tewari and Mariswamy (2013) studied teak plantations in Karnataka had evaluated heartwood, sapwood and bark content in covering different age groups (11–36 years), density (516–2061 trees/ha) and sites. Results revealed that highest heartwood proportion of stem wood volume (over-bark) was 56.3 % and the lowest was 37.1 %. The sapwood proportion and the bark content ranged from 12.9 %–23.0 % and 27.8 %–43.5 % respectively. The heartwood proportion increased with DBH but the sapwood proportion did not vary with DBH, while the proportion of bark decreased. The bark content decreased with increasing age, but increased with stand density. There was no significant difference in heartwood content with respect to age or stand density because the ages of the two stands were similar.

Anoop *et al.* (2014) evaluated the wood quality of *Swietenia macrophylla* introduced in Kerala, South India. Standard tests of wood physical, mechanical and anatomical characteristics were conducted on oven-dry specimens of five trees which were randomly selected from the research plot of the Kerala Forest Department. Results of the study indicated that the wood physical and anatomical characteristics varied along the radial directions from pith to periphery. Physico-mechanical characteristics were correlated with anatomical characteristics and most of the wood quality parameters were comparable to teak.

Dhiman (2014) studied three wood species *i.e.*, *Pinus roxburghii*, *Celtis australis* and *Bombax ceiba* by using *Acorus calamus* extract as biopreservative and observed the variation in specific gravity using Smith's formula (1954) and recorded values as 0.544, 0.586 and 0.465 respectively. It was found that specific gravity of wood samples varied with different concentrations of extract. Getahun *et al*. (2014) observed that in *Pinus patula,* tree height had significant effect on basic density with non-significant effect on initial moisture content, tangential as well as radial shrinkages. Basic density, initial moisture content and radial shrinkage have shown decreasing trend from bottom to top of log, but tangential shrinkage increased from bottom to top of the log. The value of mechanical characteristics decreased from bottom to top of log in all tests of green and dry samples.

Hedge *et al*. (2014) evaluated variation in physical characteristics of wood among some tropical tree species of South India. The specific gravity of wood of various tree species ranged from 0.14 in *Pterocarpus santalinus* to 0.96 in *Hymenodictyon excelsum*. The highest heartwood sapwood ratio was for *Tectona grandis* in case of disc from the base and hence, teak was found better among all the other species. Latib *et al*. (2014) studied the physical and chemical characteristics of Kelempayan (*Neolamarckia cadamba*) wood and reported that the highest specific gravity of Kelempayan was found at the bottom portion, followed by middle and top portion. Along the radial direction, specific gravity was highest near the bark and was followed by middle and near pit. The percentage of moisture content increased from bottom to top portion.

Okoh (2014) studied four tropical hardwood species from Ghana and its physical characteristics. These were fibre characteristics (fibre length, fibre width, cell wall thickness and lumber diameter), physical (oven-dry density) and reported that the density of timber was a function of both cell wall thickness and lumen diameter. He also studied the variation in specific gravity and shrinkage in *Gmelina arborea* wood. It was evident from the results that variations in the axial and radial directions were statistically significant for all the characteristics evaluated and hence concluded that wood of *G. arborea* should be treated as such in their conversion and utilization strategies.

Wani *et al*. (2014) observed the variations in wood characteristics among five hardwood species *i.e. Populus nigra, Parrotiopsis jacquemontiana, Salix alba, Juglans regia* and *Robinia pseudoacacia* at three different sites viz. Khrew (site-I), Surasyar (site-II) and Shopian (site-III) in Kashmir. The maximum variation in specific gravity has been recorded in *R. pseudoacacia* and *P. jacquemontiana*. On the basis of specific gravity variation patterns, these woods were categorized as light, moderately heavy and moderately heavy to heavy which predicts the characteristics like strength, dimensional stability with moisture content change, fibre yield per unit volume and suitability as a raw material for making paper. Wanneng *et al*. (2014) studied physical characteristics of *Tectona grandis* and noticed that wood density and specific gravity values of plantation teak of different ages were not significantly different. The mean values did not show relationship between wood characteristics and the age of tree. On the contrary Kim *et al*. (2011) found that fibre length and wood specific gravity significantly influenced by site and clone. Huandi *et al*. (2015) examined the growth traits of four 7-year-old clones of Poplar and studied variations in wood physical characteristics at three sites. Variation in the growth traits differed among sites also fibre traits showed significant interclonal variation and concluded that poplar has the capability to meet growing future demands.

Sharma (2016) studied the physical characteristics of wood samples of *Cedrus deodara* collected from different sites in Himachal Pradesh, India and recorded that highest specific gravity (0.5138) was recorded for the wood samples collected from Chopal site in Shimla district whereas the highest moisture content (91.09 %) was observed for wood samples procured from Nankhari site of Himachal Pradesh. Jothivel (2016) determined specific gravity of wood for a total of 71 tree species from different parts of the Kolli hills (78°20' to 78°30'E and 11°10' to 11°30' N). The specific gravity of the maximum number of species (28) analysed was found between 0.60 to 0.69, followed by 0.5 to 0.59 (16), 0.7 to 0.79 (14), 0.8 to 0.89 (8), 0.4 to 0.49, ≥ 9 (1), 0.3 to 0.39 (1) and 0.2 to 0.29 (1). The average wood specific gravity was 0.653 (ranging from 0.28 to 0.94). Among the species, *Drypetes melanoxylon* (0.94 ± 0.04) had the highest specific gravity and *Moringa oleifera* (0.28 ± 0.03) had lowest. The results revealed that the specific gravity is highly deviated; it may conclude that the study area had variation in soil composition, mean annual precipitation, seasonality and temperature.

Sunny *et al.* (2019) studied the wood characteristics of wood of *Dalbergia sissoo* wood collected from different market sites of Himachal Pradesh. The maximum moisture content of (20.170%) was observed in the wood samples of Nalagarh site. Highest specific gravity of (0.644) in Dattowal site and lowest in Nalagarh site *i.e*., 0.517. Maximum vessel diameter (0.126 mm), fibre diameter (0.020 mm) and fibre length (1.66 mm) was found in the wood samples from Ghumarwin, Dattowal and Ghumarwin site respectively.

2.2 CHEMICAL PROPERTIES OF WOOD

Wood is best defined as a three-dimensional biopolymer composite composed of an interconnected network of cellulose, hemicelluloses and lignin with minor number of various extractives and inorganics. Primarily, the wood is chemically composed of carbon, hydrogen and oxygen in which carbon and oxygen are predominant and usually about 49 and 44 % respectively, on weight basis. The remaining 7% is mostly hydrogen with small amount of nitrogen and metallic ions (ash) (Young, 2000). Wood's chemical composition cannot be defined precisely for a given tree species but varies with tree part (root, stem and branch), type of wood (*i.e*., normal, tension and compression) location, climate and soil conditions (Samkova and Nagyova, 1987). Analysis of chemical composition is used to distinguish between hardwoods (angiosperms) and softwoods (gymnosperms). Major chemical components in wood are lignin (18-35 %) and carbohydrates (65-75 %) which are complex, polymeric materials which is composed of cellulose and hemicelluloses polymers with major amount of other sugar polymers such as starch and pectin (Stamm, 1964). Minor amount of extraneous materials, mostly in the form of organic extracts and inorganic material (ash), are also present in wood (4-10 %). Overall, wood has an elemental composition of about 50 % carbon, 6 % hydrogen, 44 % oxygen and trace amounts of several metal ions. Cellulose and hemicellulose, together described as holocellulose, is a term used to denote the polysaccharides in wood. Pure cellulose consists of 'glucan', a chain molecule consisting entirely of glucose residues.

Cellulose is a natural polymer consisting of long chain of β-D-glucose formed from carbon dioxide, water utilizing energy from the process of photosynthesis and regarded as the fibre within the wood composite (Dinwoodie, 2000). Barnett and Jeronimidis (2003) estimated the length of cellulose chains to be up to 5000 nm in length and adjacent chains bonded through a combination of hydrogen bonds and Van der Waal's forces. Hemicelluloses, also known as polyose is a carbohydrate polymer is different from cellulose in many aspects, notably that it is non-crystalline and its degree of polymerization is much lower than cellulose (Siau, 1984). It consists of chain molecules similar to pure cellulose but containing polysaccharides other than glucose, such as galactose, rhamnose, aribinose, mannose and xylose (Bland, 1985).

Lignin, the final component of the composite, which is an aromatic polymer (Perez *et al.*, 2002) and along with hemicelluloses it can be thought of as forming the matrix of the composite, creating a sheath surrounding the cellulose core. The combination of cellulose (40-50%) and hemicelluloses (15-25%) are called holocellulose and usually account for 65-75% of wood dry weight (Rowell, 2013). Extract is a term used to describe a number of various chemical compounds that are contained within the wood but are not part of its essential structure. Extracts include; polyphenols, oils, fats, gums, resins, waxes and starch and named as such because they are able to be extracted by solvents (Bootle, 1983). Sapwood is commonly very low in extracts; the greatest concentration being in the outer heartwood region, while the inner region containing the juvenile core is lower. Extracts are thought to be deposited within the heartwood during the normal transformation of sapwood to heartwood, or as a response to injury or stress. The number of extracts present within a stem is quite variable between and within species (Smith, 1982). Extracts have been found to be as high as 30% in some instances typically represent 5-10% of dry wood mass, but (Bootle, 1983). A brief summary of chemical composition was given by Petterson (1984) for U.S. hardwoods and softwoods. According to which softwoods consist of 64.5±4.6% of holocellulose and 28.8±2.6% of klason lignin, whereas hardwoods consist of holocellulose (71.7±5.7%) and klason lignin (23.0±3.0%).

Wilde and Paul (1959) in the wood of *Populus tremuloides* observed only 10 per cent of variation in specific gravity and chemical composition which could be related to differences in soil on which the trees were grown. Mullins and Mcknight (1981) studied on aspen (*Populus tremuloides*) and observed the following chemical profile: cellulose 53 per cent, hemicelluloses 31 per cent and lignin 16 per cent, on extract free wood basis. Khurana *et al.* (1983) observed wood of both male and female trees of *Populus ciliata* of 18 natural provenances in temperate forest and ravines and variation in holocellulose, lignin and ash content. Narayanamurti and Verma (1964) studied the effect of hot water, alcohol benzene, ether and methanol extracts from *Dalbergia sissoo* in varying concentration on extracellular enzymes (amylase, invertase and cellulose) of *Polystictus versicolor* and *Ganoderma lucidum*. Yasin and Qureshi (1989) studied the hot and cold-water extracts of saw dust (made of bark wood) of 8 species including *Dalbergia sissoo*. The hot water solubility of shisham was found to be 9.05 per cent. The cold-water soluble extracts in all these species ranged from 1.14 to 5.18 per cent.

Manmohan and Mukhergee (1965) analysed the proximate chemical analysis of *Albizia lebbeck* and reported that ash content (0.72%), cellulose (52.47%), liginin (22.90%), pentosans (17%) and per cent yield of pulp (50.0%) through sulphate method of pulping. Kawamura and Bland (1967) observed that because of climatic changes in the tropical temperate zone, variation was found mainly in lignin content in several species of *Eucalyptus*. Unkalkar *et al.* (1975) noticed that alcohol-benzene solubility and water (cold and hot water) decreased rapidly form bottom to top in 9-10 years of *Eucalyptus* hybrid. Alcohol-benzene extracts were observed highest in lower part of the stem. Sharma and Dobhal (1969) noticed that water soluble extract and catechin content increased with age with trees aged between 15-25 years appeared to be suitable for commercial production of extracts in *Acacia catechu.* Karnik *et al*. (1971) found that the wood constitutes about 30-35 per cent of the total wood in *Acacia catechu* and carbohydrate (holocellulose) content was as high as 74 per cent and lignin content fairly low. It was also reported that the hot water solubility (7.30 per cent) of wood of khair (*Acacia catechu*) was more than cold water solubility. Singh *et al.* (1972) revealed that *Lagerstromia speciosa* and *Terminalia myriocarpa* are suitable for producing wrapping, writing and printing paper. The proximate chemical analysis of two woods indicated the presence of ash content (19, 1.1), hot water solubility (5.0, 4.9), alcohol benzene solubility (3.7, 1.7), pentosans (13.8, 14.5) and lignin content (26.3, 27.4), respectively.

Beleam and Harkin (1975) determined the lignins of hardwoods growing on southern pine sites in U.S.A. and observed that hardwoods yielded 19-20 per cent of Klason lignin content, and concluded that lignin content varied among species, among individuals and within the plant. The proximate chemical analysis of *Bambusa tulda* showed the presence of the ash content (1.29%), hot water solubility (5.57%), one per cent caustic soda solubility (20.82%), alcohol benzene solubility (1.89%), lignin content (23.70%), cellulose content (58.50%) and pentosan content of 17.80 per cent (Bhola, 1976). Laboratory experiment on the chemical analysis of *Ailanthus excelsa* indicated its suitability as raw material for pulp and paper production (Ash content

2.14%, hot water solubility 3.6%, 1% NaOH solubility 13.1% and lignin 30.08%) (Guha and Pant, 1981).

Mahmood and Khattak (1986) analysed blue pine (*Pinus wallichiana*) wood and observed lignin, holocellulose and alpha-cellulose as three major cell wall components. All these main cell wall components were determined in *Pinus wallichiana* for earlywood (juvenile wood) and latewood (adult wood) among innerwood and outerwood and at different height levels. Latewood was consistently lower in lignin content and higher in holocellulose and alpha-cellulose content than earlywood. Both earlywood and latewood from innerwood were consistently higher in lignin content and lower in holocellulose and alpha-cellulose content than that of outerwood**.** Purba and Sumarua (1987) observed the chemical composition of twenty seven wood species from west Java and recorded the cellulose content, pentosan, lignin, ash, silica, cold water extracts, hot water, 1:2 alcohol-benzene and 1 per cent NaOH was found to be 40.99 to 55.54 per cent; 12.49 to 19.54 per cent; 17.20 to 28.86 per cent; 0.19 to14.3per cent; 0.05 to 0.79 per cent; 0.11 to 7.20 per cent; 2.18 to 10.44 per cent; 0.54 to 8.70 per cent and 11.01 to 37.94 per cent respectively. Stinger and Olson (1987) revealed that total extracts contents did not vary significantly among sampling heights. However, ethyl alcohol benzene and hot water extracts content exhibited an inverse relationship to height with mean value of 3.7 per cent at ground level decreasing to 2.7 at 80 per cent of the total height of tree. Hot water extracts varied positively with height. Polar extract content (Et-OH and hot water) exhibited a positive vertical relationship, averaging 3.63 per cent at the upper crown position.

Thakur (1989) revealed that extracts, lignin, holocellulose and ash content showed significant variation among the biomass components with the age of the tree in *Robinia pseudoacacia*. Diameter at breast height (DBH) was also found to affect cold water solubility, alcohol-benzene solubility, holocellulose and ash content. Sharma (1997) reported that the lignin content has inverse relation with the height of *Robinia pseudoacacia* tree, while holocellulose and pulp yield have positive relationship with different levels of height. Deka *et al.* (1992) studied 14-year-old hybrid willow (*Salix* spp.) and reported average holocellulose and lignin content of 79 per cent and 21 per cent, respectively. Sjostron (1993) evaluated the chemical composition of different wood species and found the per cent of lignin in softwoods *i.e.*, *Pinus sylvestris, Picea glauca* and *Betula verricosa* to be 27.5, 27.7 and 22.0 per cent respectively and that of hardwoods to be (*Eucalyptus camaldulensis*) 31.3 per cent. Total extracts percentage were analysed as 3.5 per cent in *Pinus sylvestris*, 2.1 per cent in *Picea glauca,* 3.0 per cent in *Betula verricosa* and 2.8 per cent in *Eucalyptus camaldulensis*. Chatterjee *et al.* (1977) found that *Pinus roxburghii* is known to be a rich source of terpenoids, flavonoids, tannins and xanthones among other compounds and almost all the parts of plant were found to contain biologically active compounds. Ahmad *et al.* (1989) observed the different chemical constituents isolated from bark of the plant include hexacosylferulate, taxifolin, quercetin, catechin, kaempferol, rhamnetin, 3, 4-dihydroxybenzoicacid, 3, 4-dihydroxycinnamic acid, pinosylvin, pinoresinol, resin acid, sterols, gallocatechin and tannins.

Chaturvedi (1997) studied the wood of *Populus eupharatica* and the chemical analysis recorded ash content (0.73%), water solubility (1.91%) and alkali solubility (15.11%)**.** Ming *et al.* (1997) studied the 10 provenances of 10-year-old *Pinus taeda* and observed the variations in wood chemical compositions among and within provenances. No significant differences in cellulose and lignin content were found by the statistical analysis among the provenances except those of pentosan and benzene-alcohol extracts. Cellulose, lignin and pentosan content and alcohol-benzene found to be 41.47 to 43.15 per cent 28.85 to 30.10 per cent, 14.85 to 16.45 per cent and 1.45 to 2.78 per cent, respectively. The further analysis also indicated variations in extents of main chemical constituents within a given provenance of *P. taeda* were greater than those among provenances. Pari *et al.* (1997) studied nine Indonesian species and observed that holocellulose content ranged from 69.61 to 75.21 per cent, lignin from 24.79 to 39.39 per cent and specific gravity from 0.36 to 0.85. The solubility in cold water, hot water and alcohol-benzene (1:2) ranged from 4.33 to 7.41 per cent, 4.67 to 9.47 per cent and 1.99 to 9.21 per cent respectively. Upreti *et al.* (1999) observed that wood of *Pterocarpus marsupium* (bijasal) contains high content of water-soluble extracts, leaching of which restricts its outdoors use. Extract leaching was successfully arrested by treatment of wood surfaces with dilute aqueous solutions of few water repellent inorganic salts.

Raymond *et al.* (2001) found that with increasing height, the pulp yield of *Eucalyptus globules* remains constant over 70 per cent of the total height and as cellulose content increased predicted pulp yield decreases; the inverse is true for lignin content. Sun *et al.* (2001) reported that extraction of the dewaxed and partially delignified fast-growing poplar (*Populus* sp.) wood with 1.5, 3.0. 5.0, 7.5 and 8.5 per cent NaOH at 20ºC for 16 hrs was found to solubilize 65.6, 71.6, 73.8, 85.6 and 89.3 per cent of the original hemicelluloses, respectively. Fernandez *et al.* (2002) observed the potential genetic variation in quaking aspen *(Populus tremuloides* Michx.) wood extracts by sampling nine natural clones at breast height. Significant clonal differences were found not only in the levels of total acetone extracts, but also in the levels of sterols-triterpenes, steryl esters waxes and triglycerides, all of which are known to contribute to pith formation in pulping and paper making. He conducted treatment of solvent-extracted fast-growing poplar wood with 60 per cent aqueous ethanol in 0.2 M HCl at 75ºC for 3 hours released 16.7 per cent of the original lignin, and 25.5 per cent of the original hemicelluloses.

Sharma and Sharma (2003) observed that the lignin content decreased, while holocellulose content increased from ground level to the top of the tree of *Eucalyptus tereticornis*. The chemical analysis of *Eucalyptus camaldulensis* and *Eucalyptus globules* species showed that solubility in one per cent NaOH ranged from 15 to 18 per cent, respectively. Mahdavi *et al.* (2004) at Pasand research station in Mazandaran province observed cross sectional disks at breast height from three 17-year-old trees of *E. camaldulensis*. Chemical compositions of the wood consist of cellulose; lignin and extracts (in acetone soluble) were measured at 47.44 per cent, 30.87 per cent and 6.96 per cent, respectively. Gierlinger *et al*. (2004) analysed the extract content of lignin and thereby the brown-rot decay resistance against *Coniophora puteana* and *Poria placenta* in larch heartwood from different species and origin (*Larix decidua* var. *decidua, L decidua* var. *sudetica, L. kaempferi, L. eurolepis*).The extract content in treatments with cold water, 1 per cent NaOH and alcohol benzene were 4.84, 5.75, 156.98 and 6.09 per cent respectively.

Adamopoulos *et al.* (2005) analysed the variation within the stem of certain chemical characteristics of three mature 35 to 37-year-old black locust tree wood discs from the bottom, middle and top. Hot water extract content was greater in heartwood than in sapwood, while the reverse occurred for the dichloromethane extract content. Vertical stem analysis of hot-water extracts showed that they increased in heartwood but decreased in sapwood from the bottom to the top of the stems while the reversal occurred for dichloromethane extract content of sapwood. lignin content in heartwood (25.73 per cent) was greater than in sapwood (18.13 per cent) at the bottom. Lignin content of heartwood decreased from 25.73 per cent to 18.33 per cent, at the bottom to at the top, while that of sapwood was18.13 per cent, 21.42 per cent and 19.64 per cent at the bottom, middle and top respectively. As observed by Admopolous *et al*. (2005), with his study on the chemical characteristics from bottom, middle and top of three black locust tree wood discs, the lignin content at the bottom in heartwood was found greater to that of sapwood (18.13 %). The lignin content of heartwood decreased from 25.73 per cent at the bottom to 18.33 per cent at the top, while that of sapwood was 18.13 per cent at the bottom, 21.42 per cent at the middle and 19.64 per cent at the top.

Carballo *et al.* (2005) carried out a study to statistically compare the wood chemical composition of *Eucalyptus saligna, Corymbia citriodora (Eucalyptus citriodora)* and *Eucalyptus pellita* at three heights of commercial bole (25, 55 and 85 per cent) in samples coming from Forestry Companies of Macurije and Guanahacabibes in Pinar del Rio province of Cuba. The wood of *E. citriodora* presented higher cellulose contents, and lower lignin and extracts, thus considered the most attractive species, from the chemical point of view, to be used in the paper industry. Esteves *et al.* (2005) reported that in maritime pine *(Pinus pinaster* Ait.), heartwood represents a substantial part of the tree stem at final harvest age (80 years) corresponding to 42 per cent at the base of the stem wood diameter and decreasing upward. Differences in the chemical composition between heartwood and sapwood were mainly in the extracts, 19.7 per cent and 5.8 per cent, respectively. The lignin content was 23.1 per cent and 24.5 per cent in the heartwood and sapwood, respectively.

Kumar *et al.* (2005) observed variation in physico-chemical characteristics of wood of candidate plus trees (CPTs) of shisham (*Dalbergia sissoo*). The results noticed that among different CPTs of *Dalbergia sissoo*, significant differences were noticed for all the characters except for holocellulose contents. The chemical characteristics of sapwood viz., cold water solubility, hot water solubility, alcohol-benzene solubility, lignin content and holocellulose content ranged between 2.25-6.75 %, 3.50-9.15 %, 1.01-7.56 %, 23.90-30.50 % and 66.00-76.55 %, respectively while that of heartwood of *Dalbergia sissoo* CPTs viz., cold water solubility, hot water solubility, alcohol-benzene solubility, lignin content and holocellulose content ranged between 5.25-10.15 %, 9.15-11.55 %, 6.82-10.82 %, 30.50-39.70 % and 62.00-70.00 %, respectively. Fakhrian *et al.* (2005) analysed the physical, chemical, fibre dimensions, pulp and paper making characteristics of 4 years old *Alnus glutinous* and recorded in 48.5 per cent cellulose, 25.35 per cent lignin, 0.31 per cent ash as well as 2.36 per cent extracts.

Morais *et al.* (2005) analysed the chemical composition of *Pinus oocarpa* wood cultivated in the Brazilian cerrado and reported α-cellulose (59.05 per cent), hemicelluloses (21.22 per cent), lignin (25.18 per cent), dichloromethane extracts (2.78 per cent), ethanol: toluene extracts (4.38 per cent), hot water extracts (4.31 per cent) and ash (1.26 per cent). Orealgarza *et al.* (2005) observed samples came from the Forestry Company of Macurijes, Pinar del Rio, Cuba and studied the chemical composition of *Eucalyptus saligna* wood at three height levels of the commercial bole. They determined the contents of cellulose, lignin, hemicellulose, ashes, as well as extracts substances, in different solvent systems using TAPPI Norms. The results revealed great differences in the content of extracts substances increasing with the height of the bole, although the lignin increased apparently towards 85 per cent of the height of the commercial bole, due to the influence of the phenolic extracts in the lignin contents and cellulose showed structural differences with the height of the bole.

Russell *et al.* (2005) observed that, there was an effect of spacing on extracts, hemicelluose, lignin and cellulose of *Eucalyptus globulus.* Wide spacing gave the highest average values for extracts and cellulose. Narrow spacing increased the hemicellulose content whereas lignin did not have a trend from wide to narrow spacing. Bautista and Honorato (2006) analysed the chemical composition of four Mexican oak species: *Quercus coccolobifolia, Q. durifolia, Q. rugosa and Q. oleoides* and the revealed that cellulose content ranges from 46.18 to 52.94 per cent, extract content was between 1.02 to 4.83 per cent for alcohol-benzene and from 4.35 to 9.07 per cent for hot water-soluble extracts. Hernandez and Salazar (2006) determined the chemical composition of four Mexican Oak species: *Quercus coccolobifolia,* Q. *durifolia, Q. rugosa and* Q. *oleoides.* The samples of sapwood, heartwood and a mixture of sapwood-heartwood were taken from each species and used to analyze contents of cellulose, pentosans, lignin, ethanol-benzene extract, hot water extract, ash and tannin. The cellulose content was in the range of 46.18 to 52.94 per cent, amount of pentosans was from 19.08 to 20.61 per cent and lignin content was between 20.40 and 23.35 per cent. Extract content was between 1.02 and 4.83 per cent for ethanol-benzene extract and from 4.35 to 9.07 per cent for hot water extract.

Silva *et al.* (2006) observed the chemical composition variation in *Eucalyptus grandis* wood of four different ages (10, 14, 20, and 25 years) from commercial stands. The samples were avoided from three discs taken from the base and top of the first two 3 m logs, from 16 trees. The mean values of holocellulose, lignin and extracts contents were 69, 27 and 4 per cent respectively. With greater concentration near the base, the extracts and lignin contents increased with age, and the holocellulose content also decreased near the base with age, with more concentrations in discs removed from upper parts of the trunk. Barbosa *et al*. (2007) observed antitermitic characteristics of crude extracts of wood and bark of *Pouteria guianensis* and *Scleronema micranthum* found extracts levels of 2.5 per cent and 4.6 per cent, respectively. Diaz *et al.* (2007) noticed that low lignin content of a lignocellulosic material reduces pulping time and chemical charge as compared to those of other non-wood raw materials. They also reported that pulp yield is negatively correlated with extracts content (ethanol-benzene and water soluble).

Guller *et al*. (2007) observed the chemical mechanical and physical characteristics of black pine (*Pinus nigra*) and noticed that the holocellulose content increases from juvenile to maturity stage from 64.7 to 72.2 per cent while the lignin content decreases from 33 to 28.5 per cent. They also analysed the hot water and cold-water solubility of black pine and found that the hot water solubility ranges from 2.25 to 4.71 per cent in juvenile and mature wood while the cold-water solubility in juvenile wood was 3.88 per cent. The alcohol-benzene solubility in juvenile wood was 2.51 per cent while in mature wood was 6.07 per cent. Taylor *et al.* (2007) observed that beside cellulose, hemicellulose and lignin the fourth component of wood *i.e.*, extracts were non-structural substances which are soluble in organic solvents and water and these were found in the cell lumina, cellular voids and channels. Yusoff *et al.* (1992) studied the chemical composition of one, two and three-year-old bamboo (*Gigantochloa scortechinii*) and the results indicated that the holocellulose content among different ages of bamboo did not vary much whereas alpha-cellulose, lignin, extracts, pentosan, ash and silica content increased with increasing age of bamboo. The phytochemistry of the *Toona ciliata* revealed the presence of cedrelone in the heartwood, 5- methylcoumarins in the stem bark and limonoids and siderin in the leaves of the plant (Chaudhary, 2004 and Lio *et al*., 2007). Cedrelone seperated from the benzene extract of heartwood of *Toona ciliata* and yield various compounds from it by photooxidation (Gopalakrishnan *et al.*, 2000). Kumar *et al*. (2012) noticed the pharmacognostical study of leaf of *Toona ciliata* M. Roem. and revealed that the total ash values was not more than 11.5 %, acid insoluble ash values was not more than 1.4 %, water soluble ash values was not more than 4.2 %, sulphate ash was not more than 15.4 %. In case of extract values, petroleum ether soluble was 14.08 %, for chloroform soluble was 5.28 %, for alcohol soluble was 8.72 %, hydro alcoholic soluble value was 23.12 % and for water soluble was 16 %.

Lopez *et al.* (2008) stated that *Leucaena leucocephala* holds hot water soluble (4%), 1% NaOH solubles (18.4%), ethanol-benzene extracts (4.6%), holocellulose (75.9%), lignin (21.4%) and alpha-cellulose (44.4%). Raiskila (2008) observed three different Norway spruce cutting clones grown in three different environments within the boreal zone and noticed that the trees from a fertile site revealed the highest sapwood lignin content, the slowest growing clone had the lowest sapwood lignin content. Yasuo *et al.* (2008) carried out chemical analysis of *Eucalyptus globules* choosed from two plantation sites and observed that holocellulose content ranged from 85.0 to 87.7 per cent, cellulose from 44.80 to 48.3 per cent, lignin from 15.4 to 18.7 per cent and alkali extracts from 16.0 to 18.2 per cent. Szczukowski *et al.* (2008) done investigations on the chemical composition of 3-year old willow *(Salix viminalis)* rods which were created as new, fast-growing cultivars of high potentials for biomass production intended, primarily, for energetic purposes. The *Salix* genus is well known for its ease of crossing and creation of new cultivars and hybrids. The *Salix viminalis* hybrids were characterized by high cellulose content (46-51 per cent), with the exception of the *Salix viminalis* × *S. purpurea* cross in which about 43 per cent cellulose was determined. The content of lignin ranged from 22.91 to 26.97 per cent and of holocellulose from about 72 to 78 per cent. The new cultivars of bush willows gave low concentrations of soluble substances. Ximenes *et al*. (2008) observed the proportion of above ground biomass in commercial harvest of *Pinus radiata, Callitris columellaris, Eucalyptus pilularis and Corymbia maculate* and *Eucalyptus oblique* in Australia. The cellulose concentration of the wood was found to be 56-64 per cent for the hardwoods and 40-52.5 per cent for the softwoods.

Nazri *et al.* (2009) observed the effects of chemical components on characteristics of oriented strand board (OSB) from *Leucaena leucocephala* wood. The main purpose of the study was to determine basic chemical components of *Leucaena leucocephala* from 8 and 16-year-old trees and to correlate the effects of chemical components with characteristics of its oriented strand board. He observed that in his study that generally, the cold and hot water-soluble extracts of *L. leucocephala* increased from bottom to top portion of the tree. The highest value for cold water soluble was observed in the top portion (5.97%) of the 8-year-old tree and the lowest in the bottom portion (4.25%) of the 16-year-old. Similar results were noticed in case of alcohol-toluene soluble extracts, lignin content and holocellulose content, whereas the results revealed that the 8-year-old tree had higher alcohol-toluene soluble extracts, lignin content and holocellulose content compared with the 16-year-old and a clear decreasing trend was observed on the effect of age and an increasing trend in tree portion *i.e.,* from bottom to top. Yang *et al.* (2009) worked on 3-year-old culms of 8 provenances of *Bambusa chungii* from Guangdong, Guangi and Hainan Provinces and observed that there were significant differences between 1 per cent NaOH extraction contents of *B. chungii* and the heritability for 1 per cent NaOH extract and lignin were 0.54 and 0.38, respectively. A significant negative correlation was found between per cent NaOH extraction, alcohol-benzene extract contents and bamboo culms yield.

Gamboa *et al.* (2010) noticed that dichloromethane extract from the roots of exotic *Toona ciliata*, had the unusual natural compound which were identified by using spectroscopic analysis, which were limonoid cedrelone, the sterols sitosterol and stigmasterol, the coumarins isopimpinellin and siderin, the furoquinoline alkaloid skimmianine, 2-hydroxy-4-methoxycinnamaldehyde and four 9,10 dihydrophenanthrenes. Boliu *et al.* (2011) also had observed the chemical constituents of the leaves and stems of *Toona ciliata* var. *pubescens* using silica gel column chromatography and structures were identified on the basis of spectroscopic data and chemical evidence. Almost 23 compounds were isolated from the 95 % ethanol extract of the leaves and stems of *Toona ciliata* var. *pubescens* and their structures were identified as siderin.

Hindi and Bakhaswain (2010) observed the valorization for fibre production of eight Saudi lignocellulosics: *Phoenix dactylifera* (surface fibres, leaflet and rachis) and wood from each of *Conocorpus erectus, Leucaena leucocephala, Simmondsia chinensis, Azadirachta indica* and *Moringa peregrina* were investigated. Fibre length, specific gravity, chemical composition, total extracts, lignin, holocellulose and ash content of the eight lignocellulosic materials were determined. *Leucaena leucocephala* was noticed to be the best resource due to its high content of holocellulose (70.82 %), its reasonable fibre length (1.13 mm) and to its specific gravity (0.59) approaching those of other hardwoods and its low contents of total extracts (9.74 %), lignin (18.86 %) and ash (1.22 %) compared to the other resources examined.

Adi *et al.* (2011) observed the fiber and chemical characteristics of branchwoods of three *Meranti* species namely *Meranti* Sangkan, *Meranti* Bakau, and *Meranti* Bungakulit Hitam from Bukit Batu Peat Swamp Forest, Riau. The results showed that holocellulose contents of *Meranti* Sangkan, *Meranti* Bakau, and *Meranti* Bungakulit Hitam were 72.97 per cent, 75.28per cent, and 69.88 per cent, whereas the α-cellulose contents were 43.55 per cent, 51.14 per cent, and 43.25 per cent, respectively. *Meranti* Sangkan had the highest lignin content (35.99%) followed by *Meranti* Bakau (34.21%) and *Meranti* Bungakulit Hitam (32.18%). *Meranti* Bungakulit Hitam had the highest extract content (2.24%) followed by *Meranti* Sangkan (1.66%) and *Meranti* Bakau (1.08%). Al-meffarej *et al.* (2011) done the spacing trials in *Tectona grandis* which gave the highest average values of extracts, cellulose and ash contents; 8.92 per cent, 46.90 per cent and 2.53 per cent, respectively. The narrow spacing reported maximum average values of hemicellulose (21.05 %) and lignin content of wood did not show a trend from wide to narrow spacing. Kasmani *et al.* (2011) revealed that by increasing tree age, the amount of cellulose, extracts and lignin increased but the number of hemicelluloses and ash decreased in *Eucalyptus camaldulensis.* Mohammadi *et al.* (2011) also observed similar results for the same species. Kiaei and Samariha (2011) observed Ailanthus *altissima* wood (trunks and branches) and reported that in trunk wood element of cellulose, lignin, extract alcohol benzene and ash were 47.18, 25.19, 3.5, and 1.25 per cent, respectively, whereas, for branch wood the corresponding values were 44.12, 23.86, 3.2 and 1.75 per cent, respectively. The amount of cellulose and lignin in the trunk wood and branch wood when compared with other types of wood suggested that relatively high pulp yield can be obtained.

Donmez *et al.* (2012) analysed the chemical composition of different coniferous species cones growing naturally in Turkey, for this the cones of eleven species from Pinaceae family and three species from family Cupressaceae were collected and the level of holocellulose of the cones was determined between 40.08-63.54 per cent in all species. The hot water solubility of *Cedrus libani* cones was 7.63 per cent, cold water solubility was 3.93 per cent, alcohol solubility was 13.42 per cent, holocellulose content was 63.44 per cent and lignin content was observed to be 30.79 per cent. Miranda *et al.* (2012) observed the bark of *Eucalyptus globulus* for kraft pulping under industrial condition and it was noticed that bark had less favorable chemical composition with more extracts as compared to wood, especially polar extracts (5.3% Vs 1.6%) and 1% NaOH solubility (19.9% Vs 12.2%), pentosan (23.7% Vs 21.3%) and ash (2.9% Vs 1.0%), although the fiber length was higher (1.12 mm Vs 0.98 mm). The kraft pulp obtained using bark revealed significantly lower yield, delignification degree and strength characteristics but had a quicker response to refining.

Poletto *et al*. (2012) studied the wood chemical characteristics of four species namely, *Dipteryx odorata and Mezilaurus itauba*, *Eucalyptus grandis and Pinus elliottii.* The holocellulose content was determined to be around 63 per cent for

Eucalyptus grandis, 61 per cent for *Pinus elliottii* and 57 per cent for both *Dipteryx odorata and Mezilaurus itauba.* The *Pinus elliottii* had the highest lignin content with around 34 per cent while *Mezilaurus itauba* had the lowest with 28 per cent, while lignin content of *Dipteryx odorata* and *Eucalyptus grandis* was noticed to be 30 per cent and 32 per cent respectively. The study on extracts, holocellulose, alpha-cellulose, lignin and ash content in cultivated tropical bamboo (*Gigantochloa brang, G. levis, G. scortechinii and G. wrayi*) was carried out by Wahab *et al.* (2013). Their culms exhibited different chemical composition in the contents of extracts, holocellulose, alpha-cellulose, lignin and ash between the bamboo species, location in the culms and position at the nodes and internodes. The extract content of three selected species of bamboo varies from 8.00 to 9.23 per cent. The holocellulose content for *G. levis* were 85.08 per cent, *G. wrayi* 84.53 per cent, *G. brang* 79.94 per cent and *G. scortechinii* 74.62 per cent. The α-cellulose were higher *in G. brang* (51.58%), followed by *G. scortechinii* (46.87%), *G. wrayi* (37.66%) and *G. levis* (33.80%). The lignin contents were higher in *G. scortechinii* (32.55%), *G. wrayi* (30.04%), *G. levis* (26.50%) and lowest in *G. brang* (24.83%). The percentage of ash content were 2.83 per cent, 2.83 per cent, 1.29 per cent and 0.88 per cent in *G. scortechinii*, *G. levis*, *G. brang* and *G. wrayi* respectively.

Barauna *et al.* (2014) observed that in "amapá" wood (*Brosimum parinarioides* Ducke), the average holocellulose content was 63.3% and agrees with those obtained by Browning (1963), who noticed the holocellulose content of the amazon wood "paumulato" (*Qualea dinizii*), "abiurara" (*Lucuma dissepala*), "breubranco" (*Protium heptaphyllum*) and "imbaúba" (*Cecropia juranyana),* and recorded the values ranging from 69.3% to 73.8%. The values observed in the chemical characteristics of "amapá" wood are close to those observed by Barauna *et al.* (2014), who took into consideration the same species, but in other longitudinal position. The average value of the lignin content (30.51%) was observed to be consistent with the value obtained by Miller (1999), who recorded lignin concentration ranging from 23 to 33 per cent. The percentage of total extracts in the "amapá" wood (5.31%) were also observed to be consistent with those cited in the literature for Amazonian woods.

Latib *et al.* (2014) in his study on physical and chemical characteristics of Kelempayan (*Neolamarckia cadamba*) wood. The samples for chemical determination were taken from the bottom, middle and top portion of the trees. The chemical composition of Kelempayan wood was determined for cold and hot water solubles, alkali solubles, alcohol toluene solubles, ash content, lignin content and holocellulose content. The cold-water solubility values range from 5.54% to 5.75% and the highest average value for cold water-soluble extracts was observed in the middle portion (5.75%) and the lowest in the top portion (5.54%) of the tree. The hot water solubility ranges from 6.03% to 6.94% and the highest average value for hot water was observed in the top portion of the tree (6.94%). The middle portion of the tree gave the lowest hot water soluble having average value of 6.03%. The alcohol-toluene soluble content ranged from 2.24 to 2.58%. The maximum and minimum alcohol toluene content was recorded in the top portion and from the middle portion *i.e.* 2.58% and 2.24% respectively. The lignin content was recorded in the range of 24.58 to 30.92% irrespective of portion from tree. The maximum value was observed at the top portion (30.92%) while the minimum value in the middle portion (24.58%) of the tree. The holocellulose content was observed in a range from 82.11 to 84.84%. The maximum holocellulose content was observed in the top portion (84.84%) while the lowest was recorded at the middle portion (82.11%) of the tree.

Sunny *et al.* (2020) observed the variation in the chemical characteristics of *Artocarpus heterophyllus* wood procured from three altitudinal zones of Thrissur district, Kerala. The characteristics like cold water solubility, hot water solubility, alcohol benzene extracts, cellulose, hemicellulose, holocellulose, klason lignin, NaOH soluble extracts and ash content are being determined for which the highest value obtained are 3.40%, 7.11%, 13.91%, 44.33%, 29.12%, 71.42%, 28.21%, 21.48% and 0.80% respectively.

2.3 ANATOMICAL PROPERTIES OF WOOD

Wood anatomy, the concept of proportion and distribution of the microstructure especially is very important to wood identification and utilization (Seralde, 2006). The density variation between species is primarily due to differences in anatomical structure. Species differ with regard to cell types and the distribution of these cells within the wood. One of them very important in hardwood is “Fibre” which provides strength to wood. Reviews regarding wood anatomical features are discussed below:

Bisset *et al*. (1950) observed the fibre length variation within one growth ring in teak. These workers reported that the increase in the fibre length was rapid and a more or less constant value was reached quite quickly. Kedharnath *et al*. (1963) observed significant variation in fibre length in the three regions across the stem in teak provenance test at Haldwani, (U.P.). The fibres in the sapwood region when compared with than those in the adult-heart wood region were noticed significantly longer, and those in adult-heart wood region were significantly longer than those in the juvenile heartwood region. They also observed significant differences in fibre length were also between trees within each region of the sample cores. The pulping of *Albizia procera* revealed that pulp from Whites iris could be made by sulphate process. The average fibre length of the pulp was 0.90 mm and the average diameter was 0.021 mm. Easy bleaching pulp and good yield with satisfactory strength characteristics could be prepared from *Albizia procera* (Guha, 1969).

Rays are groups or strips of parenchyma cells which are horizontally aligned running in a radial direction from pith or centre of a log to the bark or periphery and are meant mainly for radial conduction and storage. They are present in all woods and are visible on the end surface as numerous, fine, whitish, or light coloured parallel lines at right angles to the growth marks. On the tangential surface, they appear as spindle shaped bodies arranged with their long axis vertical (Rao and Juneja, 1971). Purkayastha *et al.* (1980) did the wood quality assessment studies on *Eucalyptus tereticornis* plantations raised in different localities in north and south India concluded that coefficient of variation of specific gravity in five plantations was about nine per cent while no significant difference in fibre characteristics was observed in three out of four plantations. Bhat *et al*. (1990) analysed wood density and fibre length of *Eucalyptus grandis* and estimated average density as 495 kg m^{-3} with no significant increase up to nine years of age while fibre length increased consistently with age. Sidhu and Rishi (1997) concluded in their work on 18 years old *E. tereticornis* that thickness of heartwood, bark and pith significantly decreases at higher bole heights from the base.

The principal element that are responsible for the strength of the wood are fibres (Panshin and Zeeuw, 1980) and the major factor governing density and strength in wood is the thickness of the fibre cell wall. The species with thin-walled fibres such as cottonwood (*Populus deltoides*) have a low density and strength and are therefore preferred for light construction purposes, whereas species with thick-walled fibres have a high density and strength which have made them useful in heavy construction work. With or without abundance of tyloses, crystals, gum and resins, some hardwood species are thin-walled, some are of medium size, while others are thick-walled. Ghouse and Iqbal (1983) observed cell size variation in *Acacia nilotica* and revealed that the length of vessel segments decreased from base to top and later stabilizing in the old trunk. After an initial increase, the length of xylem fibres became more or less constant. Wu and Wang (1988) observed the variation in fibre length and cell wall per centage along the height of the tree was analysed in *Acacia mangium* and *Acacia auriculiformis* trees. Also, similar studies were carried out by Ku and Chen (1984) in the above two *Acacia* species.

With a view to investigating whether there is any significant difference, the study was undertaken by Purkayastha *et al*. (1984) in the average fibre length of *Eucalyptus tereticornis* different plantation of the same age class. The fibre length in three out of four plantations (Shahdol-805 µm, Bangalore-790 µm and Coimbatore-804 µm) revealed no significant difference, only the Dehra dun grown trees the average value was significantly lower (742 µm). Robinson and Mize (1987) noticed that the fibre length of European black alder provenances ranged from 0.68 to 1.01 mm and relative density ranged from 0.37 to 0.42 g/cm^3. There was no significant difference between provenances for either trait. Ewers and Fisher (1989) stated that liana vessels are considered to be the longest and widest in the plant kingdom. Larger diameter stems showed longer as well as wider vessels (*Pithecodenium crucigerum*) in certain tropical and subtropical lianas during cellular examination.

Bhat *et al*. (1990) in tropical Indian hardwoods growing in Kerala noticed considerable variation in fibre length within the tree, including branches. Branch fibres were significantly shorter then stems fibres and radial pattern of fibre length variation in their study, in the majority of the species gave a decline in fibre length near the bark after an initial increase from the pith to outwards. Chuil and Peters (1995) revealed that the fibre length of the juvenile wood of European larch was shorter than that of the mature wood and Raymond *et al*. (1998) observed the fibre length of *Eucalyptus regnans* has changed little over the first 30 per cent of total height, but changed significantly over the remaining height. Pan *et al*. (1998) observed genetic variation on fibre length in willow (*Salix*) nursery stock of different hybrids and clones. They noticed significant differences in fibre length of clones at saplings stage and also found differences in fibre diameter and fibre length among different ages of same clones.

Fahn and Werker (1990) observed that large vessels are not obligatory in lianas and quite a significant number possess small vessels. For eg. *Carissa ovate* and *Quintinia fawkneri* have mean vessel diameters of 44 µm and 60 µm, respectively. Such a decrease in vessel diameter in lianas is covered up by an increase in vessel frequency so that, the proportion of vessels remains more on an average than in trees. By combining large vessel diameter with fibres, it is possible to maintain high conductivity and mechanical resistance whose walls provide the resistance required of the tissue as a whole (Tyree *et al*., 1994). Bhat (1994) observed the physical and cellular characteristics of wood of some less known tree species from Kerala. He took into account several families and analyzed their textural and colour characteristics. For Fabaceae family, he revealed that the wood was hard, coarse textured with straight or interlocked grain. Sapwood was narrow, yellowish white and heartwood yellowish or olive brown in colour, having fine straight to wavy tangential markings of soft tissue.

In pulp manufacture, strength characteristics are worked out in part by fibre length. And increased fibre length leads to the production of paper with increased strength. During the manufacturing process, the increased fibre length increases the strength of wet webs enabling easier handling (Seth, 1995). However, long fibres are not considered for all applications and in some cases, shorter fibres are preferable, such as in the production of smooth-surfaced papers. The fibre characteristics vary between species, and consequently particular species have been limited historically to particular applications. Fibres from hardwood species are generally much shorter than those from softwoods and this result in the production of pulp and paper with desirable surface characteristics such as smoothness and brightness, but with minimum strength characteristics. In practice, where a single species is providing fiber with a combination of characteristics has not been available, the mixing of long and short fibre from different species is used. If a single source is available, possessing the desirable characteristics plus optimal fibre length, this would be of great benefit to the processor.

Gartner *et al.* (1997) observed that the variations between the two heights and between the lower and upper sides of the lean of red alders *(Alnus rubra* Bong.) were minor or not significant for all measured characteristics. In the radial direction, fibre length and vessel diameter increased rapidly during the first 8 to 12 years (from 0.8 to 1.2 mm and 47 to 60 mm, respectively). From pith to bark, there was no significant change in ray proportion, a small increase in the vessel proportion (from 23 to 28%), and a small decrease in the fibre proportion (from 63 to 57%). Specific gravity was constant radically and with height but varied significantly among trees (from 0.45 to 0.51 for tree means). These results suggest that the wood characteristics of *A. rubra* are quite uniform within individual trees with the exception of fibre length and vessel diameter, which increase radically in the first several growth rings**.**

Idu and Ijomah (1998) observed that variations in vessel width are significant for identification purposes in closely related species. The vessels are of considerable relevance not only for their primary roles but also for impregnation of wood with chemicals for preservation and pulping. Vessel width projects significant variation along the stem vertical axis. Lev (1998) noticed the relationship between ray density and ray height in early wood of *Pinus haplensis* and *Pinus pinea.* He discovered that all the trees of *Pinus* species showed gradual tendency for increase and decrease in ray number and ray height from pith to periphery. The studies on basic density and cellular characteristics of *Eucalyptus camaldulensis, E. citriodora, E. paniculata* revealed that basic density was 651, 716 and 720 kg/m^3 for *E. camaldulensis, E. citriodora* and *E. paniculata,* respectively. Fibre length was 0.96, 0.94 and 1.00 mm, fibre wall thickness was 4.93, 4.80 and 5.88 mm and fibre lumen diameter was 5.58, 5.38 and 4.47 mm for *E. camaldulensis, E. citriodora* and *E. paniculata,* respectively (Hamza, 1999).

Vessel morphological characteristics are very much dependent on environmental factors and plays a crucial role in the wood formation and development. Varghese *et al*. (2000) observed the variation in growth and wood traits among nine populations of Teak in peninsular India and noticed a significant variation in the size of vessel elements of the sample collected from Kalakkad (Tamilnadu) and Allappally (Maharashtra). Vessel size is expected to affect growth positively because the water transporting capacity of vessels increases with their diameter to the fourth power according to Hagen-Poiseuille's law (Hacke and Sperry, 2001). Chauhan *et al.* (2001) observed variations in specific gravity and wood anatomy in 10-year-old trees of 18 clones of *Populus deltoides,* collected from experimental plantations in Uttaranchal, India. The specific gravity pojected maximum at 50 per cent tree height and fibre length at 25 per cent of tree height showing a decreasing trend upwards. The fibre length and specific gravity at breast height increased rapidly up to the 6th year followed with a tendency to level off by a slower rate of increase up to the 8^{th} year. The breast height values of specific gravity and fibre length were highly correlated with whole tree values for these two parameters.

Cox *et al.* (2001) analysed the growth and wood quality of four dipterocarp species (*Shorea acuminata*, *S. ovalis, S. leprosula* and *Dryobalanops aromatica*). Trees were randomly selected from a taungya plantation that was established in Kenaboi Negeri Sembilan, Peninsular, Malaysia. A detailed study of *S. ovalis* revealed that mean fibre length was 1355 µm. The specific gravity ranged from 0.31 (*S. leprosula*) to 0.37 (*S. acuminata*). The positive association between vessel diameter and climate is usually depicted as reflecting a response to environmental conditions. The conductively efficient and wide vessels are seen as adaptations to moist conditions, with more cavitation resistant narrow vessels expected to be favored in drier areas (Carlquist, 2001; Tyree and Zimmermann, 2002). An important factor potentially interfering with ecological trend in vessel diameter is age (Corcuera *et al*., 2004) and to maintain a favourable water balance, when the tree is growing and increasing its leaf surface, trees usually produce longer and wider vessels in their stems with age (Cruizi *et al*., 2002).

Larger diameter vessels are more efficient, while the opposite is true for vessels with small diameter (Alves and Angyalossy, 2002). Since it is also related to the woods with higher or lower mechanical resistance, vessel diameter should not be linked with sap transport only. Therefore, large diameter vessels can lead to weaker woods when compared to woods with smaller diameter vessels. Rao *et al*. (2002) observed within tree variation in cellular characteristics of *Eucalyptus tereticornis* clones. Vessel frequency, vessel diameter and fibre length were noticed to vary significantly from bottom to top with no definite trend. The fibre length was positively correlated with fibre diameter and double wall thickness.

Susilawati and Fujisawa (2002) made the first and second round selection of plus tree candidates of *Eucalyptus pellita* seedling seed orchard (SSO) in Pleihari, South Kalimantan based on growth performance (phenotype). Based on wood samples collected, the family performance evaluation in wood characteristics was from progeny test aged 66 months (5 years 6 months). The samples were separated out by diameter class (large, medium and small), and a total of 8 family for each class diameter were selected, resulting in 24 families for the whole 10 blocks. Wood density and fibre length of *E. pellita* revealed high family heritability, which ranged from 0.385 to 0.565 for wood density and 0.155 to 0.569 for fibre length. The estimation of mean values of wood density of total section varied from 0.53 to 0.68 and the fibre length of total section varied from 0.76 mm to 1.06 mm.

Rao *et al*. (2003) observed the radial variation in cellular characteristics of plantation grown *Tecomella undulata*. They noticed that vessel frequency, vessel diameter and percentage of solitary vessels were interrelated and significantly varied from pith to periphery. Zuo and Wen- Zhong (2003) revealed significant variation in wood density among poplar clones and observed that there was significant difference in wood basic density among the growth rings, which has an increase tendency along the direction from the pith. The mean wood basic density had a general increase trend with increasing height of the trees and they also observed significant variations in fibre diameter and the ratio of fibre length to diameter among poplar clones. There were significant differences in fibre length and fibre diameter among the growth rings, which had an increasing tendency along the direction from pith to bark. The fibre length and fibre diameter had a general decline trend with increasing height of the trees.

Jiang *et al*. (2004) observed fourteen fast growing poplar varieties widely cultivated in Shandong Province, China, for their volume growth, fibre shape, chemical composition and economic indices. The average fibre length and fibre content in the 6-year-old stand of the 14 poplar varieties was 0.863-1.051 mm, which was equivalent to 51.37-58.17 per cent. Liu *et al*. (2004) observed the physico-mechanical characteristics (density, shrinkage ratio, compression strength perpendicular to grain) of *Hippophae rhamnoides* and determined that the mean of fibre length was 601.48 µm and air density was 0.574 g/cm^3. Pande *et al*. (2004) studied Red *Meranti* group of *Shorea* in Malay Peninsula on the inter-species variations in the different wood elements. The variance ratio test revealed that variations in the wood elements *viz*., fibre-length, vessel-diameter and wall-thickness were significant due to species. These variations were non-significant due to samples of same species (alpha =0.05) and the minimum specific gravity was observed for *S. dasyphylla* (0.368) while maximum recorded for *S. macrantha* (0.848). The dimensions of different wood elements were non-significantly correlated to each other and it was well documented by wood technologists that the dimensions of wood fibre of a species vary in different climatic conditions which have direct impact on wood quality. Temperature affects the relationship between fibre wall thickness and fibre lumen and the number and size distribution of xylem vessels in seedlings and mature trees (Thomas *et al*., 2004).

According to Anoop *et al.* (2005), the wood of jack tree has vessels which are solitary and in radial multiples of two to three and the individual vessel outlines appeared to be circular in shape. The vessel element length ranges from 300 µm-530 µm with a mean of 400 µm with tangential diameter of vessel element ranges from 160 µm-270 µm with a mean of 220 µm. Parenchyma arrangement in the wood of jack tree is paratracheal, with aliform or confluent nature. Rays are multiseriate ranging from 370 µm-890 µm in height with a mean of 610 µm and the fibres are thin walled and non-septate. Fibre walls tend to be thicker in drier environments (Luchi *et al*., 2005) because a stronger wood is necessary to support negative xylem pressures which reflects that thicker cell wall make the wood less vulnerable to cavitation and collapse. Xylem of affected trees are characterized by the presence of crystalliferous fibres developed in the latewood and the development of such fibres was not found in normal trees. Considerable structural variations also occurred in the xylem of affected trees. Pan *et al.* (2005) observed the wood cellular characteristics of 24-year-old hybrid tulip (*Liriodendron chinense* x *L. tulipifera*) and revealed an average fibre length of 0.80-1.74 mm. The fibre length from pith to bark increased rapidly, tended to stabilize at the 9th to 11th year growth ring. Rahman *et al.* (2005) observed that teak trees having highest ray volume showed higher specific gravity and greater compression strength irrespective of the fact that ray proportion remains the same across pith to bark.

Venkaiah *et al.* (2006) analysed twenty clones of *Populus deltoides* for wood characteristics at the end of 9th year. The clone '5-18' gave the maximum specific gravity (0.427) and clone 'C-181', the minimum value (0.333). The longest fibres were observed in the clone 'IC'(1.236 mm), closely followed by 'A-238' (1,222 mm), the shortest fibre length (0.952 mm) was recorded in '6-17'. Wang *et al.* (2006) observed and analysed the key fibre morphological features, fibre length, fibre width, cell wall thickness, ratio of length to width, and ratio of cell wall to lumen of poplar *(Populus deltoids* 1-69/55). In the radial variance, from the pith outward, the fibre length, fibre width and ratio of length to width all increased year after year, reaching a maximum at a certain year and then, decreased gradually. Wang *et al.* (2006) analysed and recorded key fibre morphological features, fibre length, fibre width, cell wall thickness, ratio of length to width, and ratio of cell wall to lumen of poplar (*Populus deltoids* 1-69/55). The results observed that in the radial variance, from the pith outward, the fibre length, fibre width and ratio of length to width all increased year after year, reaching a maximum at a certain year and then, decreased gradually**.** Schmitz *et al.* (2006) observed the vessel triats in relation to salinity in mangroves and concluded that environmental responsiveness of vessel diameter to soil water salinity was remarkably low in either rainy or dry season. However, the average vessel diameter appears just as clearly predicted by water availability across habitats and the variation in the diameters of vessels, is thought to be of central to adaptive importance (Sperry *et al*., 2006).

Christensen *et al*. (2007) revealed the cellular and mechanical characteristics of six species of tropical trees with two different rooting morphologies. They observed that the smallest vessels and the lowest vessel frequency were found in the parts of the trees subjected to the greatest stresses or strains. A tradeoff between conductivity and stiffness or strength was carried out, which revealed that cellular alterations occur in response to mechanical strain. Jiang *et al.* (2007) observed that the wider spacing for *Populus xiaohei* may feasibly increase the rate of wood production while not affecting fibre length for pulpwood production. This was concluded by analysing the effects of stand density on wood quality of this species. Significant variation of pulp yield and basic density of different *Eucalyptus* species *viz.*, *Eucalyptus grandis*, *Eucalyptus amplifolia* and *Corymbia torelliana* was earlier reported by Rockwood *et al.* (2008).

Krisdianto and Damayanti (2007) observed that the cellular characteristics and fibre dimensions of *Acacia nilotica*. They characterize timber as dark brown heartwood which is clearly distinct from sapwood and they observed that the length of wood fibres decreases from pith towards periphery portion. They concluded that *Acacia nilotica* wood has second class quality of fibre, which shows that its fibre is moderately thick with narrow lumen diameter and hence wood of this species can be used for construction purposes. Pande *et al.* (2007a) studied the different species of *Shorea* of White *Meranti* group of the Malay Peninsula and observed the variations in physical, macroscopic and microscopic cellular features. Variance ratio (F) test revealed that interspecific differences among wood element dimensions of *Shorea* were significant for fibre length, vessel element length, wall thickness and fibre diameter. However, intra-specific differences were non-significant for all the cellular characters for which the fibre diameter and vessel element length gave positive significant correlation. Pande *et al.* (2007b) also observed the variations in physical, gross and minute cellular features of different species of the *Balau* group in the Malay Peninsula. Variance ratio (F) test revealed that interspecific variations among the wood element dimensions of studied species of *Shorea*, were significant while intraspecies variations were non-significant for all the characters. Similarly, Pande *et al.* (2007c) observed the variations in physical, gross and microscopic cellular features of different species of *Shorea* of Yellow *Meranti* group of Malay Peninsula.

Variance ratio (F) test revealed that inter-specific differences among the wood element dimensions of *Shorea* were significant for vessel element length, wall-thickness and fibre-diameter and non-significant for fibre length and wood density (α=0.05). However, intra-specific differences were non-significant for all the cellular characters. The vessel element-length and diameter showed negative while wood density showed positive correlation with fibre wall thickness.

Vessel lumen diameter (VLD) is another property which is having significant importance in wood cellular studies and the vessel lumen diameter generally shows radial variation from centre to bark region. The studies observed that similar variation trend for vessel lumen diameter, *i.e.* the vessel lumen diameter increases from pith to outwards. Tsuchiya and Furukawa (2008, 2009) observed the relationship between radial variation in vessel lumen diameter and the stages of the radial growth in two species namely *Castanea crenata* and *Quercus serrata* and analysed that vessel lumen diameter increased during the early and the middle stage and become stable in the later stage. Chowdhury *et al*. (2009) observed the radial variations of wood characteristics in 11-year-old *Acacia auriculiformis* grown in Bangladesh. They noticed that fibre length and fibre length increments increased up to about 80 mm radial distance from pith and then were almost constant towards the bark. They also observed that uniform wood formation starts after a certain radial distance from the pith. The variation in fibre length also indicated that the wood property variation in the species was radius dependant.

Nguyen *et al.* (2009) observed the growth, specific gravity, and wood fibre length of *Acacia mangium, Acacia auriculiformis*, *Acacia* hybrid clones, and combinations, which were planted in a trial forest in Bavi, Vietnam. The superiority of hybrids over their parents ranged from 36.3- 41.6 per cent for diameter, from 6.9- 20.7 per cent for specific gravity, and from 6.1- 12.8 per cent for wood fibre length. Wood fibre length was initially 0.5-0.6 mm near the pith and then finally slowly increased, ranging 1.0-1.2 mm near the bark and the specific gravity of *Acacia* increased from 0.49-0.58 near the pith to 0.63-0.47 near the bark. Pande *et al.* (2009) observed the intra and interspecies variations in the dimensions of different wood elements and wood density of *Balau*, White *Meranti* (*Meranti Pa'ang*), Yellow *Meranti* (*Meranti dammar hitam*) and the Red *Meranti* group of Malay *Shorea*. Variance ratio (F) test showed that intra-species differences of *Shorea* were non-significant for all the groups. The inter-species except vessel element diameter, variations were prominent for fibre length, fibre diameter, wall thickness and vessel element diameter for all the four groups for White *Meranti* and fibre length for Yellow *Meranti*. In case of wood density, significant variations were noticed for all the groups except in the Yellow *Meranti* group (α=0.05) with the wall thickness, fibre diameter, wood density and vessel element length were positively correlated (α=0.05).

Ramirez *et al.* (2009) had observed the wide range of variations in *Eucalyptus globules* clones for vessel frequency, vessel area and vessel coverage among the clones. From pith to bark, mean vessel area and vessel coverage increased gradually except the fact that vessel frequency decreased. Pande and Singh (2009) observed that within tree, intra and interclonal variations in wood cellular characteristics of 4 years old clonal ramets of *Eucalyptus tereticornis* Sm. Radial variations in all the individual ramets were found to be non-significant for all cellular characteristics investigated, while interclonal variations were significant. Wani and Khan (2010) had observed significant variation in the wood cellular features viz. fibre length, fibre diameter, fibre wall thickness from different positions of trees of *Populus nigra* L.

Pande and Dhiman (2010) carried out comparison between intraramet, intraclonal and interclonal variations in fibre length, fibre diameter, wall thickness, vessel element length in the ramets of clones of *Populus deltoides* at the age of 6 years old produced from planting material grown by macro and micro-propagation techniques. The tests revealed that intraramet variations were non-significant for all the characters and in general wood element's dimensions increased from bottom to top and pith to periphery radial locations. Wani and Khan (2010) observed significant variation in the wood cellular features viz. fibre length, fibre diameter, fibre wall thickness from different positions of trees of *Populus nigra* L. Lal *et al.* (2010) observed the fibres of *Anthocephalus cadamba* as short but its fibre width, cell wall thickness, and rigidity coefficient are comparable to those of softwood such as *Pinus kesiya* and *Picea abies*. Due to low lignin and higher holocellulose contents, *A. cadamba* produces high pulp yield at milder cooking conditions.

Anoop *et al*. (2011) observed the variation in wood characteristics of *Artocarpus heterophyllus* Lam., *Artocarpus hirsutus* Lam. and *Pterocarpus marsupium* Roxb. raised as part of a provenance trial of the Kerala Agricultural University at the Livestock Research Station, Thiruvazhamkunnu, in Palakkad district of Kerala. The results showed higher values for ray height, ray width, vessel frequency in *A. hirsutus*, when compared to the other two species while, *P. marsupium* had the highest air dry and oven dry specific gravity. *A. heterophyllus* had superior values for vessel diameter, vessel area, fibre length and fibre diameter. The data procured from this study indicates that the potential of these hitherto under-estimated multipurpose indigenous species for various end uses and also points to the pertinent need to undertake long term tree improvement trials of the above species for efficient utilization of these promising species for the state of Kerala.

Adi *et al*. (2011) compared the fiber characteristics of branchwoods of 3 *Meranti* species namely *Meranti* Sangkan, *Meranti* Bakau, and *Meranti* Bungakulithitam from Bukit Batu Peat Swamp Forest, Riau. The result revealed that fiber length of *Meranti* Bungakulithitam, *Meranti* Sangkan, and *Meranti* Hitam were 1475.45 μm, 1475.45 μm, 1442.62 μm, and 1205.23 μm, respectively. Dutt and Tyagi (2011) had studied the 11 *Eucalyptus* species for their morphological, pulp and paper making characteristics and observed that *Eucalyptus grandis* of Bhadrachalam and Saharanpur origins gave very good fibre dimensions, especially slenderness ratio. The other *Eucalyptus* species had shorter fibres and narrow lumen with thick wall resulting in poorer flexibility, higher runkel ratio and rigidity coefficient. El-Juhany (2011) evaluated the wood quality of *Melia azaderach* in terms of fibre length, specific gravity and heartwood/sapwood area. The results revealed that the fibre length varied between trees and ranged between 0.742 and 0.797 mm and increased from pith to bark, ranging between 0.62 and 0.92 mm. The specific gravity did not vary among trees, but increased from pith to bark with both fibre length and specific gravity increased from the pith to bark.

Izekor and Fuwape (2011) observed *Tectona grandis* wood in Edo state, Nigeria and observed that the mean values of fibre length were 1.45, 1.73 and 1.96 mm; fibre diameter, were 26.79, 29.47 and 32.83 micro meter; fibre lumen width were

18.17, 15.60 and 14.15 micro meter, while the mean values for fibre wall thickness were 5.87, 7.89 and 9.80 micrometer for 15, 20 and 25 year old *Tectona grandis* wood, respectively. Fibre length, fibre diameter and cell wall thickness increased with increase in age while fibre lumen width decreased with increase in age and all these cellular characteristics decreases from the base to top and increased from innerwood to outerwood. Naji *et al.* (2011) observed that vessel characteristics in *Hevea brasiliensis* (Rubber) were more or less influenced by tree spacing. Dewi and Supartini (2011) investigated wood anatomy of *Shorea cuspidata* (P.S. Ashton) in order to ensure this species belongs to Yellow *Meranti* group. Such study is very important since this species is already listed in the red list of IUCN and classified as critically endangered species. The results revealed that the main microscopic characters are vessel diffuse, mostly solitary, rounded to oval; simple perforation plate and alternate intervessel pits; parenchyma scanty paratracheal to thin vasicentric; axial intercellular canals in long tangential line, radial intercellular canal and vasicentric tracheids present; rays uniseriate and multiseriate, prismatic crystal in procumbent cells; fibre length 1,294 µm, diameter 26µmand wall thickness 4µm. The confirmation of species which belongs to Yellow *Meranti* group was done by macroscopic and microscopic observation of wood. The analysis on fibre dimensions and derived values of the wood fibres classified the wood into class quality II which shows that this species is moderately favorable as raw material for pulp and paper manufacture.

Pande and Dhiman (2011) observed variation in wood cellular characteristics and specific gravity of *Populus deltoides* Bartr. ex Marsh. They showed that the fibre length increased with height and dimensions of wood elements and specific gravity also increased from pith to periphery. For average specific gravity values, significant radial variation has been observed where these variations may be related to age. Tavares *et al*. (2011) had analysed wood and bark fibre characteristics of *Acacia melanoxylon* and *Eucalyptus globules* and noticed that wood and bark fibre length varied between 0.90-0.96 mm and 1.33-1.59 mm respectively. The cell wall thickness varied between 3.45-3.89 µm in wood and 5.02-5.40 µm in the bark. The wood and bark fibre length decreased from the bottom to the top of the tree but cell wall thickness had no specific pattern for axial variation. The fibre length and wall thickness increased from the pith to bark and with some fluctuations, the wall thickness slightly increased. In *A. melanoxylon* significant site differences were observed in relation to bark fibre length and wood wall thickness. The fibre of *A. melanoxylon* was thinner, while the bark fibre was thicker and the radial variation was similar in both species. The fibre wall thickness increased from the base to the middle of the tree height in the wood of *E. globules,* and decreased to the top; in the bark decreased from the base to the top. The study of cellular characteristics of *Leucaena leucocephala* wood and its effect on oriented strand board was carried out by Nazri *et al.* (2012) showed that except for the number of vessels, the cellular characteristics were affected by age. As the age increased from eight-year-old to sixteen-year-old, the ray width increased by 21 per cent and the number of ray cells also exhibited significant differences. Cellular and histochemical studies of jacktree revealed that ray parenchyma was multiseriate consisted with 2-4 layers of rays and ray parenchyma showed abundant starch content. The xylem ray parenchyma cells contained more protein than the wood fibers and phloem parenchyma cells (Islam *et al.,* 2012). They also observed the presence of perforated ray cells in uniseriate to multiseriate rays in the wood of *Heuchera sanguinea* is important and such cells usually connect vessels located at opposite sides of the ray and function as conducting elements. Angyalossy *et al*. (2012) found that these cells are known to occur in lianas. Clara (2012) carried out the experiments on *Eucalyptus urophylla* with the spacing of 2.00 m × 3.00 m, 2.25 m × 3.00 m, 2.50 m × 3.00 m, 2.75m × 3.00 m and 3.00 m × 3.00 m with densities of 1666, 1481, 1333, 1212 and 1111 trees ha^{-1}, respectively. Among the different spacing treatments, the maximum fibre length was observed in 3.00 × 3.00 m treatment (811 µm) and observed to be superior over other treatment. It was also noticed that effect of spacing did not influence significantly the vessel diameter and vessel frequency in *Eucalyptus urophylla*.

Pande *et al.* (2012) studied the 6-year-old *Populus deltoids* and observed the interclonal variation in dimensions of wood elements and specific gravity of based on sexual dimorphism of a female clone (G48) and male clone (G3). The Variance ratio (*F*) test indicated that both clones differed significantly in fibre length and diameter, wall thickness, vessel element length and diameter, and specific gravity. The G48 clone revealed higher fibre and vessel element dimensions but lower specific gravity than G3 clone, suggesting better fibre dimensions for G48 and specific gravity for G3 and observed female dominance on wood cellular characteristics. From pith to periphery the fibre length and specific gravity increased with height, the dimensions of wood element and specific gravity also increased. Intraramet variations for both the clones were observed non-significant which shows that homogeneous wood characteristics could be achieved from the single bole. Intraclonal variations in G48 revealed non-significant differences, suggesting stable wood characteristics in the clone.

Adeniyi *et al*. (2013) observed the utilization of some species in relation to their cellular features. The microscopic characteristics such as rays, vessels and fibre dimensions were related to the other characteristics such as the mechanical characteristics. They noticed that some hardwood species were thin walled, some of medium size, while others were thick-walled, with or without abundance of tyloses, crystals, gum and resins. So, in different areas of application, the features exhibited by various wood species have made the Nigerian wood species useful. Saravanan *et al.* (2013) observed differences in cellular characteristics *viz.*, vessel length, vessel diameter, vessel arrangement, vessel frequency, ray height, ray width, ray frequency, fibre length, fibre diameter, fibre wall thickness and fibre lumen width of one, two, three, four and five-year-old *Melia dubia* cav. The wood samples were systematically collected from the pith, middle and periphery wood sections of the radial positions. They had also observed mean values for one, two, three, four and five year old *M. dubia* wood and determined the vessel length (235.68, 250.72, 272.76, 292.01 and 329.57 µm), vessel diameter (192.57, 207.11, 231.10, 247.54 and 276.96 µm), vessel frequency (4.00, 4.00, 4.00, 5.00 and 5.00 mm^2), ray height (336.65, 356.56, 377.82, 399.15 and 438.23 µm), ray width (71.73, 77.00, 84.53, 91.73 and 98.66 µm), ray frequency (7.00, 8.00, 8.00, 10.00 and 11.00 /mm^2), fibre length (647.00, 825.00, 892.78, 1093.92 and 1159.30 µm), fibre diameter (24.00, 24.90, 26.01, 26.75 and 27.52 µm), fibre wall thickness (4.07, 5.29, 6.49, 7.62 and 9.08 µm) and fibre lumen width (15.87, 14.32, 13.03, 11.52 and 9.35 µm) respectively. All parameters showed significant increment with respect to increase in age and also all the cellular characteristics examined in this study increased significantly from pith to periphery except lumen width.

Singh *et al.* (2013) carried out the study on four species of *Terminalia* namely *T. arjuna*, *T. belerica*, *T. chebula* and *T. myriocarpa* to study variations in their wood elements. Mean minimum and maximum vessel diameter, vessel element length, vessel lumen diameter, fibre length, fibre diameter, fibre wall thickness, ray height, ray width and inter-vessel pits were determined as 122.05 ± 23.4 μm (*T. arjuna*) to 216.5 ± 54.43 μm (*T. myriocarpa*), 310.2 ± 125.4μm (*T. arjuna*) to 482.0 ± 125.8 μm (*T. chebula*), 10.4 ± 3.0 μm (*T. chebula*) to 27.8 ± 4.9 μm (*T. myriocarpa*),162.5 ± 273.9 μm (*T. chebula*) to 1176.0 ± 263.3 μm (*T. arjuna*), 125.4 ± 40.5 μm (*T. chebula*) to 256.9 ± 59.4 μm (*T. myriocarpa*), 1.8 ± 0.8 μm (*T. chebula*) to 2.3 ± 0.9 μm (*T. arjuna*), 179.2 ± 60.5 μm (*T. myriocarpa*) to 251.8 ± 97.6 μm (*T. chebula*), 23.2 ± 5.8 μm (*T. belerica*) to 27.7 ± 6.0 μm (*T. chebula*), 7.62 ± 1.52 μm (*T. belerica*) to 13.9 ± 9.2 μm (*T. myriocarpa*). Minimum and maximum vessel frequency were observed as 2 per mm^2 (*T. myriocarpa*) and 14 per mm^2 (*T. chebula*).

Anoop *et al.* (2014) observed that wood physical and cellular characteristics of *Swietenia macrophylla* varied along the radial directions from pith to periphery and they also correlated physico-mechanical characteristics with different cellular features. Hietz *et al*. (2015) carried out elemental analysis in vessels of *Toona ciliata* and depicted X-ray images which clearly showed the vessels and to some extent affect micro-densities. In toon, the ring boundaries are characterized by larger vessels in earlywood with abrupt changes in wood density and they were mostly identified by thin parenchyma bands around it. Heinrich and Banks (2006) observed that because of large latitudinal distributions of *Toona ciliata* it can be expected that its wood anatomies also vary because of shifts in the environmental conditions of the respective climate zones they grow in and they also came across several examples of false rings and difficult ring-boundary zones, for instance, zones of very narrow tree rings in *T. ciliata*.

Saravanan *et al*. (2014) observed differences in cellular characteristics of *Melia dubia* at different age gradations and the variation in fibre length was statistically significant among the different age gradations of wood sample. With this, they concluded that wood fibre length increases with increase in age. Jorge *et al*. (2000) noticed that with increase in age, from pith to periphery there was an increase in fibre length. Sharma *et al.* (2014) carried out studies on the cellular characteristics of *Terminalia myriocarpa* collected from plantation located at Ungma village in Mokokchung district of Nagaland. The mean range of fibre length, vessel length, increment in fibre length and wood density were observed to be 736.68μm -1300.03 ± 33.56μm, 341.10μm -431.44 ± 14.71μm, 381.31 μm -825.85 ± 19.60 μm and 0.33-0.53 ± 0.38 respectively. ANOVA which was done among trees gave non-significant variation in all the wood characteristics. Wood density, fibre length and fibre length increment increased from pith to 40 mm and afterwards it remained more or less constant and there was gradual increase in vessel length from pith to bark. The boundary between juvenile wood and mature wood could be marked at 40mm on the basis of radial variation in wood characteristics, from pith for all selected parameters. Toong *et al*. (2014) carried out the prediction of wood characteristics from cellular characteristics in common commercial Malaysian timbers and stated that cellular characteristics of the wood, namely vessel diameter, vessel grouping, vessel per square millimetre, fiber thickness, ray width, ray height, and ray per millimetre, were the factors that determined the characteristics of the wood. Vessels are vertical series of cells with open ends placed one above the other and are multicellular conduits that vary in length both within and among species. Vessel dimension was one of the major parameters studied in wood cellular investigations.

Isabel *et al*. (2015) studied the variations in wood anatomy and fibre biometry of *Eucalyptus globulus* genotypes with different wood density noticed that trees with high density had thicker fibre cell walls, lower fibre lumen width, higher runkel ratio and higher coarseness than low density trees. In the high-density group, cell wall thickness, fibre length, coarseness and runkel ratio are significantly superior. Sreevani and Rao (2015) observed that within tree variation in cellular characteristics of clones of *Eucalyptus tereticornis.* Fibre and vessel characteristics were observed and noticed to vary significantly from bottom to top with no definite trend. The results obtained in this study have revealed the suitability of raw material for paper and pulp. Maiti *et al.* (2015) observed large variation in fibre cell morphology and its dimensions among 30 species of woody plants in Northeastern Mexico and its possible relation to wood quality and its utility. It is expected that strong wood or strong paper pulp are produced from species having long fibres. The species having more wall thickness are expected to produce strong fibre through high lignification.

Phongkrathung *et al*. (2016) carried out studies on wood cellular characteristics of the family Anacardeaceae and permanent slides of wood sections and tissue maceration were made. They observed that the wood was diffuse-porous with more solitary pores and few multiple pores. Vessels were round to oval shaped and arranged in tangential bands and a diagonal pattern. It was noticed that the wood of all species had indistinct growth rings and fine textured and straight grain. As the wood of this genus has low density and hardness, it may not be suitable for heavy construction. Tripati *et al*. (2016) took into account cellular characteristics of teak for evaluating its suitability as a structural timber. Cross-section revealed large early wood pores delimited by a line of parenchyma and smaller latewood vessels; tangential section showed uniseriate and multiseriate rays and septate fibres whereas radial section has simple perforation plates, parenchyma strands and rays. So, teak can be regarded as a better species for structural works due to parenchyma strands and length of fibres.

2.4 MECHANICAL PROPERTIES OF WOOD

The mechanical properties of wood define its fitness and ability to resist applied or external forces which tends to deform it in any manner and these characteristics in turn determine the use of wood for structural, building purposes and innumerable other applications. Through experimentation either in the employment of wood in practice or by means of testing in the laboratory the mechanical characteristics are determined. All mechanical characteristics which define the use as a timber are closely related to density and thus with the distrıbution of parenchymatous tissues and vascular bundles. As mechanical characteristics of wood show the ability of wood to resist various types of external forces, static or dynamic, which may act on it (Sekhar, 1988; Panshin and Zeeuw, 1970). Mechanical characteristics are very much crucial in the case of constructional and structural purposes and these characteristics not only vary within tree but also within individuals, with reference to the nature of their fibre structure but also with the moisture content, temperature and defects of wood. According to varying conditions of growth, methods of testing and methods applied, these characteristics vary sometimes. The composition and structure of cellular elements, along with a high relative density of the fibrovascular bundles, give rise to high mechanical characteristics per unit mass and this in turn, results in mechanically efficient natural structures (Panshin and Zeeuw, 1970).

Barefoot *et al.* (1964) observed that the various mechanical characteristics of wood are controlled by the physical and anatomical characteristics such as wood density, grain angle, tracheid length, and microfibril angle of the S_2 layer in the cell wall. The factors responsible for the variations in the mechanical characteristics of the entire stem ate the changes in at least five different structural levels from the biochemical composition of the cell wall to the integral level which deals with the proportion and distribution of bending resistant and bending flexural material within the plant stem (Speck *et al.*, 1996). Goker (1977) observed the characteristics of mature black pine (*Pinus nigra*) wood and physical characteristics determined to be as follows: density 0.560 g cm^{-3}, oven dry density 0.530 g cm^{-3} and volumetric shrinkage 13.7%. The bending strength and compression strength were noticed to be 109.6 and 47.9 N/mm^2 respectively. Shukla and Kamdem (2007) observed the mechanical characteristics of red pine (*Pinus resinosa*) and noticed that MOR ranging from 55.28 to 51.62 MPa, MOE from 5.94 to 5.43 GPa and compressive strength perpendicular to grain from 8.69 to 8.02 MPa.

Sanwo (1986) carried out studies on plantation grown teak in Nigeria and observed that the rate of growth has no significant influence on specific gravity and strength characteristics. The very heavy and moderate thinning schedules did not alter the strength characteristics of teak in India and Myanmar (Kadambi, 1972)**.** Sahri *et al.* (1998) studied *Acacia mangium* and *Acacia auriculiformis* from two different provenances, Papua New Guinea and Queensland, Australia and observed the physical and mechanical characteristics. The results revealed that the species and provenances affect the specific gravity and the mechanical characteristics of the samples. *A. auriculiformis* recorded better performance than *A. mangium* and the results also revealed that the Papua New Guinea provenance was superior for both species. Shukla *et al*. (1989) studied the *Populus ciliata* timber obtained from Theog Division, Himachal Pradesh and determined physical and mechanical characteristics.

They noticed that the density and strength characteristics variation from pith to periphery in 15-yr old plantations, bottom to top variation of strength characteristics in 10-yr old G3 clones. Shukla *et al.* (1996) carried out studies on the effect of different preservative formulations/retention on strength characteristics of *P. deltoides*. Overall, it has been observed that *P. ciliata* from Himachal Pradesh can be used for plywood, laminated veneer lumber (LVL), laminated doors and windows compressed wood and fibre board.

Sahri *et al*. (1998) studied the mechanical characteristics of *Acacia mangium* and *Acacia auriculiformis* from different provenances. They noticed that the specific gravity and the mechanical characteristics of the samples were affected by the species and provenances and from all sites, *A. auriculiformis* recorded higher physical and mechanical characteristics and performed better than *A. mangium*. Gunduz (1999) observed the characteristics of Camiyani black pine (*Pinus nigra*) wood and revealed that the physical characteristics to be as follows: Density 0.590 g cm^{-3}, oven dry density 0.550 g cm^{-3}, volume weight 0.47 g cm^{-3} and volumetric shrinkage 10.2%. The bending strength and compression strength were determined to be 119.9 Nmm^{-2} and 56.93 Nmm^{-2} respectively. Elzaki and Khider (2013) observed the wood of 25-year-old *Pinus radiata* D. Don. from Jebel Marra area Western Sudan, and noticed that the average value for the oven-dry wood density (529.0 kgm^{-3}) for the Western Sudanese pine was lower than that for the Southern Sudan pine (600 kg m^{-3}) and nearer to the California pine (515 kg m^{-3}). The compressive strength was more than both Southern Sudan and the California pines and the shear stress was lower than that of the American pine. Macchioni (2001) observed that the physical and mechanical characteristics of Atlas cedar (*Cedrus atlantica)* wood from southern Italy and before mechanical testing, the samples were subjected to controlled environment in order to reach the 12 per cent moisture content. The mechanical tests were carried out on a 20 tons hydraulic computer controlled universal testing machine (UTM). The mean of Modulus of Elasticity (MOE) was observed to be 10101 MPa, modulus of rupture (MOR) was 94 MPa and compression was determined as 48.8 MPa.

Sheng *et al.* (2001) carried out studies on physical and mechanical characteristics of larch wood (*Larix spp.*) and compared with different planting density L21, L22 and L23. Some physical and mechanical characteristics of larch wood such as growth rate and latewood percentage showed result as L23>L21>L22. When dry-through, rate drying shrinkage along the grain and across the grain and volume drying shrinkage rate showed L23>L22>L21. The mechanical characteristics such as bending strength, compressive strength along the grain, overall or local compressive strength across the grain revealed considerable differences, and compressive strength along the grain, bending rigidity modulus, overall or local strength compressive strength along the grain showed L23>L22>L21.

Lindstrom (2002) observed that there was variation in wood composition, structure and wood characteristics. The wood species which are commercially important thus require careful study and analysis to know its physical, chemical, anatomical and mechanical characteristics in relation to the uses. *Cedrus deodara* have life span of 115-317 years and it's an important timber species having Modulus of Elasticity and modulus of rupture which were ranged from 56000 to 98000 kg/cm^2 and 450-630 kg/cm^2 respectively (Anonymous, 1970; 1972). Alipon *et al*. (2004) studied the mechanical characteristics of big-leafed 7 years old mahogany (*Swietenia macrophylla* King) and teak (*Tectona grandis*) plantations with 10 years old plantations respectively. Generally, the strength characteristics of 7-year-old mahogany and teak thinnings were lower than those of 10-year-old, and hence the wood of mahogany thinnings can be used for furniture and cabinets, bodies of musical instruments, whereas it was not possible to obtain lumber dimensions for cabinets and furniture from thinning at 7-year-old plantations due to their small log diameter.

Bhat and Priya (2004) observed the influence of provenance variation on wood characteristics of teak from the Western Ghat region of Southern India and noticed that bending stiffness (MOE) and maximum stress (MOR) were high in slow grown teak (65-year-old) from Konni region (Kerala) with greater per centage of cell wall. However, Rahman *et al*. (2005) observed that teak trees having maximum ray volume showed higher specific gravity and greater compression strength irrespective of the fact that ray proportion remains the same across pith to bark. Izekor *et al.* (2010) carried out studies on the effects of density on variations in the mechanical characteristics of plantation grown *Tectona grandis* wood aged 15, 20 and 25 years. They noticed that the mean density values on oven dry weight and volume basis as

480, 556 and 650 Kg m^{-3}, modulus of rupture as 76.86, 103.95 and 134.69 N mm^{-2}, Modulus of Elasticity as 6846.92, 9920.54 and 12845.57 N mm^{-2}, compressive strength parallel to grain as 43.74, 58.47 and 75.36 N mm^{-2} for age 15, 20 and 25-years old wood. Scanavaca and Garcia (2004) found out the physical and mechanical characteristics of the wood of 19-year-old *Eucalyptus urophylla* wood. The physical characteristics include basic density and mechanical characteristics such as strength in compression parallel to the grain, tangential shear strength to the growth rings, modulus of rupture and Modulus of Elasticity in static bending. These results revealed that the species had medium to high mechanical strength, high shrinkage and moderately heavy and the species was more suitable for carpentry (its structure) than for furniture.

Sharma *et al*. (2005) observed significant difference in mechanical characteristics of *Eucalyptus tereticornis* wood when using different propagation techniques in a study of 10-year-old seedling and coppice. The studies indicated that the timber from both non-coppiced and coppiced wood can be classified as very heavy, strong, tough, very hard but liable to warp and crack badly. Won (2005) determined the mechanical behavior in bending due to variation of deflection rates and he observed that the Modulus of Elasticity (MOE), modulus of rupture (MOR) and stress at proportional limit were in proportion to the logarithm of deflection rates and the deflection of wood at rupture in bending increased as deflection rates decreased. In the case of largely deflected wood by maximum bending load, severe and abundant microscopic deformations were observed. Marki *et al.* (2005) analysed the wood of the yew (*Taxus baccata* L.) related to its high density which has long been known for its toughness and strength and they determined selected mechanical characteristics of yew wood and compared with Norway spruce wood (*Picea abies*). The characteristics taken into account for study were: Modulus of Elasticity, bending strength calculated from sound velocity and resonance frequency, fracture toughness and impact bending strength. The mean bending strength of yew wood was observed to be one and a half times more than that of spruce wood. Also, the impact bending strength of yew wood was significantly higher and the fracture toughness was twice as high compared to the corresponding values for spruce wood.

Aydin *et al.* (2006) studied the mechanical characteristics of 4 timber species (poplar, fir, pine and hornbeam) commonly used in Turkey. The compressive strength, flexural strength and toughness were observed for both perpendicular and parallel to the grain and it was observed that loading direction affects all mechanical characteristics remarkably. Among the timbers tested, maximum and minimum mechanical performances were obtained with the two hardwoods, *i.e.* horn beam and poplar, respectively. The mechanical performance of the softwoods, *i.e.* fir and pine was between that of the two hardwoods. Hui *et al.* (2006) observed the mechanical characteristics of *Bambusa wenchouensis*, a sympodial bamboo compared with Moso bamboo, *Phyllostachys edulis*. The results revealed that its tensile strength parallel to grain, compressive strength parallel to grain, cleavage strength (C) and Modulus of Elasticity in static bending (MOE) were 238.0 MPa, 75.1 MPa, 45.6 N/mm^2 and 12.6 GPa, respectively, which were larger than or almost equal to those of Moso bamboo. Its shearing strength parallel to grain and bending strength were found lower and this study could lay theoretical foundation for proper utilization of *B. wenchouensis*. Kumar *et al*. (2006) observed physical and mechanical characteristics of *Acacia mangium* of nine years old obtained from Sirsi, Karnataka. The results determined has been classified as heavy, moderately strong, not tough and moderately hard after comparing with *Tectona grandis* (teak).

Shanavas and Kumar (2006) observed the mechanical characteristics of three locally important fast-growing tree species (*Acacia auriculiformis*, *Acacia mangium*, and *Grevillea robusta)* occurring as scattered and boundary planted trees on the agricultural lands of Kerala and reported that species and sample positions exerted a profound influence on the mechanical characteristics of wood. The wood density of *A. auriculiformis* was greater than that of *A. mangium* and *G. robusta*, while the moisture content followed a reverse sequence: *G. robusta* > *A. mangium* > *A. auriculiformis*. The parameters like work to limit of proportionality and work to maximum load in static bending, compressive stress at limit of proportionality in parallel to grain, compressive stress at limit of proportionality in perpendicular to grain, and end-hardness of *A. auriculiformis* were also greater than the values determined for teak (*Tectona grandis*) taken as control. However, the physical and mechanical characteristics of *A. mangium* and *G. robusta*, except shrinkage, were inferior to teak.

Ashaduzzaman *et al.* (2007) observed the mechanical characteristics of four locally important fast-growing timber species (*Acacia auriculiformis, Albizia richardiana, Dalbergia sissoo* and *Samanea saman*) occurring in homestead forests of Khulna region in Bangladesh. Significant variation was noticed for the wood density both in green and oven-dry conditions and mechanical characteristics *i.e.* modulus of rupture (MOR), Modulus of Elasticity (MOE) and screw withdrawal resistance in tangential, radial and end surface showed among the four species. The wood density of *D. sissoo* was greater than that of the other three species and followed the order, *D. sissoo* > *A. richardiana* > *A. auriculiformis* > *S. saman*. The parameters such as density in green and oven-dry conditions of *A. auriculiformis, A. richardiana, D. sissoo* were greater than the values determined for teak (*Tectona grandis*) but the mechanical characteristics of the four focal species were inferior to teak.

Aydin and Yardimci (2007) estimated the density (g/m^3) of poplar, fir, pine and hornbeam as 0.334, 0.328, 0.365 and 0.532 respectively and also determined the compression parallel to grain (MPa) for poplar (18.2), fir (32.3), pine (26.9) and hornbeam (48.3), compression perpendicular to grain (MPa) for poplar (1.9), fir (2.6), pine (2.2) and hornbeam (10.0) and Modulus of Elasticity (MPa) for Poplar, Fir, Pine and Hornbeam as 5860, 13810, 12750 and 15620 respectively. Shukla *et al.* (2007) evaluated the physical and mechanical characteristics of plantation grown trees of *Acacia auriculiformis* from Karnataka, India. They observed that MOR, MOE and MCS increased with tree age. It has been noticed that the suitability of even 8-y-old Acacia in strength as a beam was better than Teak. The shock resistance ability of older trees was comparable to that of teak whereas surface hardness and shape retention was higher in older trees of Acacia than teak.

Gurau *et al.* (2008) observed the mean values obtained for branch wood with the stem wood and estimated the moisture content in beech wood 15.4% (stem) and 33.8% (branch), maple tree 11.8% (stem) and 16.9% (branch) and scots pine 15.3% (stem) and 20.9% (branch). The density (Kg/m^3) at 12% moisture content in three wood species was observed as, beech 669 (stem) and 805 (branch), maple tree 598 (stem) and 678 (branch) and scots pine 586 (stem) and 492 (branch). Also compressive strength (MPa) at 12 % moisture content was recorded as in beech wood

49.6 (stem) and 49.3 (branch), maple 55.2 (stem) and 51.5 (branch) and in scots pine 56.6 (stem) and 31.8 (branch).

Krauss (2009) studied on the correlation between the mechanical characteristics and wood density. It had been found no functional relation between the parameters describing mechanical characteristics of the cell wall and the wood density. The greatest differentiation in the values had been noted for the tensile strength and among the coniferous species of similar density the differences have reached 113% on average, while among the deciduous species 143%, at the differences in density being only of 15%. Shirneshan *et al*. (2009) analysed the mechanical characteristics of *Salix alba* as compared to *Morus alba, Ulmus carpinifolia* and *Platinus orientalis* and observed the highest values for shear strength (4.5±0.16 MPa) in *Morus alba* followed by *Ulmus carpinifolia* and *Platinus orientalis*. *Salix alba* found to have lowest value of shear strength with 1.6±0.06 MPa. The mean values of shearing force for the five species ranged widely, with a 20-fold difference between the highest (255.8± 13.8 N; *Platinus orientalis*) and lowest (13.2±0.7 N; *Salix alba*).

Birbilis and Mantanis (2010) observed the mechanical characteristics of Athel wood (*Tamarix aphylla*), one of the least studied non-commercial wood species. Athel wood's air and oven dry densities were observed as 0.73 and 0.66 g/cm^3 respectively, whereas maximum tangential shrinkage and swelling were observed to be 10.8 and 12.1 per cent, respectively. The volumetric shrinkage and swelling were estimated at 14.0 and 15.5 per cent, respectively. Modulus of rupture, Modulus of Elasticity, compression strength parallel to grain and hardness (perpendicular to grain) values were recorded to be 88.5 N/mm^2, 7533 N/mm^2, 40.9 N/mm^2 and 33.7 N/mm^2 respectively. Izekor *et al*. (2010) observed the effects of density on variations in the mechanical characteristics of plantation grown *Tectona grandis* wood aged 15, 20 and 25-years. They observed that the mean density values on oven dry weight and volume basis were 480, 556 and 650 Kg m^{-3}, moduli of rupture were 76.86, 103.95 and 134.69 N mm^{-2}, moduli 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-years old *Tectona grandis* wood. Kiaei (2011) noticed that the wood basic density, wood oven-dry density, fiber length and cell wall thickness increase along the radial axis from pith to bark in anatomical, physical and mechanical characteristics of pine in Kelardashat region. Rahman *et al*. (2005) observed that teak wood with highest ray volume have higher specific gravity and greater compression strength while the ray proportion remains the same across pith to bark.

Marella *et al*. (2010) carried out research on mechanical characteristics of some Indian hardwoods including (Mango, Neem, Peepal, *Casuarina*, *Eucalyptus*, *Acacia*, Subabool, Kadam, Teak and Sal, etc.). The tensile strength and compression strengths were measured at normal dried condition and significant variation in mechanical characteristics was noticed with respect to each species as well as same species of same botanical family. They both were related to density, wood sample with high density revealed high mechanical strength. In their study they concluded that *Acacia nilotica* showed compressive strength which was comparable to *Tectona grandis*. Moya and Munoj (2010) analysed the mechanical characteristics of eight fast-growing plantation species in Costa Rica and found that all species behave differently. The significant decrease in specific gravity with increasing tree height was observed in *Acacia mangium.* The lowest values were measured for shear strength parallel to fibres in *Terminalia oblonga* and the highest for tension strength perpendicular to fibres in *Swietenia macrophylla*.

Ali (2011) observed that all the parameters of mechanical characteristics *viz*., static bending, compression parallel to grain, compression perpendicular to grain, hardness and shear parallel to grain, nail withdrawal, cleavage and toughness except shear parallel to grain have lower values in both green and air-dry conditions for jackfruit (*Artocarpus heterophyllus*) wood as compared to teak. Ashaduzzaman *et al.* (2011) studied the wood of Mahogany (*Swietenia macrophylla* King.) grown in homestead forest of Bangladesh analysed the mechanical characteristics. The observations were done following the standard test methods and comparing the findings with those of standard Chittagong Teak (*Tectona grandis*). It was observed that the average green volumetric shrinkage 6.62 per cent, moisture content was 39.83 per cent and densities in green, air-dry and oven-dry conditions were 0.53, 0.55 and 0.56 gm/cm^3, respectively. The average MOE and MOR valued for air-dry and oven-dry conditions as 7712.71 and 7912.12 MPa, and 71.15 and 73.59 MPa, respectively.

The compression parallel to grain and perpendicular to grain in air-dry and oven-dry conditions were 52.65 and 55.90 MPa, and 13.45 and 14.42 MPa, respectively.

Carrillo *et al*. (2011) analysed the wood characteristics of fourteen native species from Northeast Mexico with regard to their basic density (BD), Modulus of Elasticity (MOE), and modulus of rupture (MOR), as well as the relationships between these three characteristics. Results revealed that the BD range was 0.48 g cm^{-3} $\pm$0.06 to 0.93 g cm^{-3} $\pm$0.07, the minimum for *Leucaena leucocephala* and the maximum for *Condalia hookeri*. MOE range was 6.42 GPa $\pm$1.23 to 15.13 GPa $\pm$2.72, corresponding to *Diospyros texana* and *Acacia schaffneri*, respectively. Range of MOR was 101 MPa $\pm$16 to 207 MPa $\pm$33 for *Parkinsonia texana* and *Acacia schaffneri,* respectively. Kiaei (2011) observed the variations in mechanical characteristics of Elm wood (*Zelcova carpinifolia*) along longitudinal direction. The mechanical characteristics like modulus of rupture (128.93 N/mm^2), Modulus of Elasticity (9738.05 N/mm^2), compression parallel to the grain (29.73 N/mm^2), compression perpendicular to the grain (12.33 N/mm^2), shear parallel to the grain (14.19 N/mm^2) were determined. Analysis of variance (ANOVA) observed that the stem height had significant effect on Modulus of Elasticity, while it has no effect on other mechanical characteristics and these characteristics decreased along longitudinal direction from the base to bole height.

Kiaei and Samariha (2011) carried out studies on the physical (oven dry density) and mechanical characteristics (modulus of rupture, Modulus of Elasticity, compression parallel to the grain) of five hardwood plants namely oak (*Quercus castaneaefolia*), beech (*Fagus orientalis*), hornbeam (*Carpinus betulus*), alder (*Alnus glutinosa*) and ash (*Fraxinus excelsior*). The maximum wood density, modulus of rupture, Modulus of Elasticity and compression parallel to the grain values were found in hornbeam, beech, ash, and oak, respectively. The minimum mechanical strength characteristics was observed in alder wood. Miranda *et al*. (2011) observed the wood quality of *Tectona grandis* trees from an unmanaged forest and the wood characteristics of teak such as 607 kg/m^3 basic density with 3.5% and 5.2% radial and tangential shrinkage, 141 N/mm^2 modulus of rupture, 10684 N/mm^2 Modulus of Elasticity, and 50 N/mm^2 maximum crushing strength in compression parallel to the grain. They revealed that disturbances on individual tree growth were due to higher within-tree variability of ring width. However, the longitudinal and radial variations of wood density and mechanical characteristics were of low magnitude and in a degree that did not negatively impact on timber quality.

Olufemi and Malami (2011) observed the bending strength of *Eucalyptus camaldulensis*. The average density and bending strength of wood were 977.58 Kg/m^3 and 133.33 N/mm^2. High density values place the wood at position of suitability enabling to compete with some other commercial timber species and they concluded that *Eucalyptus camaldulensis* was a promising species for timber industry. Sadegh *et al*. (2011) observed mechanical characteristics (compression strength parallel to the grain and static bending strength) of beech wood and revealed that the mean compression parallel to the grain was 685 kg cm^{-2} and static bending strength 1292 kg cm^{-2}. They observed that variations in the mechanical characteristics were due to different factors, such as growth conditions and ecological factors in the same species. In particular, exposure, altitude, soil and climate conditions could affect the mechanical characteristics of wood as low density of the trees was related to higher altitude. Prihatmaji *et al*. (2011) observed the mechanical property of timber for Javanese timber house and they tested 288 specimens made from six tropical timber species and revealed that all of tropical timber specimens showed strong relationship between Young's modulus (E) and density. Jati (*Tectona grandis*), Nangka (*Artocarpus heterophyllus*), Sonokeling (*Dalbergia latifolia*), Ketepeng (*Terminalia catappa*) and *Acacia* spp. had similar increasing mechanical characteristics, while in the case of specimen Falcata, mechanical characteristics were stagnant. They also observed that smaller density means the smaller MOE. Falcata wood has minimum mechanical property and Sonokeling wood was the maximum in radial direction. *Acacia*, Jati, and Nangka had similar trend of increased Young`s modulus and yield stress. They also suggested that *Acacia* and Nangka to substitute Jati for Javanese wooden house reconstruction.

Ali *et al.* (2012) observed that all the parameters of mechanical characteristics (static bending, compression parallel to grain, compression perpendicular to grain, hardness, and shear parallel to grain; nail withdrawal, cleavage and toughness) except shear parallel to grain have the minimum values in both green and air-dry conditions for jackfruit (*Artocarpus heterophyllus*) wood as compared to teak. Awan *et.al.* (2012) observed the mechanical characteristics of *Eucalyptus camaldulensis* in comparison to conventional timbers *i.e*., *Dalbergia sissoo* Roxb., *Acacia nilotica* Del. and *Cedrus deodara* Roxb. They also noticed that *Cedrus deodara* act as good commercial timber with excellent mechanical characteristics viz. static bending (821 kg/cm^2), tensile strength (503 kg/cm^2), impact bending (661 kg/cm^2), nail holding capacity (142 kg/cm^2), maximum compression parallel to grain (91 kg/cm^2) and maximum compression perpendicular to grain (60 kg/cm^2). The mean values of wood density, static bending, MOR, maximum compressive strength parallel to grain and perpendicular to grain, maximum tensile strength, impact bending and nail holding capacity of *E. camaldulensis* were observed as 0.681 g cm^{-3},1046 kg cm^{-2}, 88 kg cm^{-2}, 56 kg cm^{-2}, 610 kg cm^{-2}, 578 kg cm^{-1}, 129 kg cm^{-1} respectively.

Hossain and Awal (2012) carried out studies on the physical characteristics, strength and durability of some timber species namely Teak (*Tectona grandis*), Sal (*Shorea robusta*), SilKorai (*Albizia procera*), Rain Tree (*Samanea saman*), Jam (*Syzygium spp*.), Jackfruit (*Artocarpus heterophylus*), and Mango (*Mangifera indica*). The test results showed that Sal, Teak and Jam were the best species for using as compression member while Sal and Teak noticed the best performance in tension. In static bending Sal, Sil Korai, Teak and Jam have been observed suitable. Sapari *et al.* (2012) observed the bending strength characteristics of off-cut Yellow *Meranti* wood by applying the finger jointed techniques. The finger orientations that were used in this study were vertical and horizontal finger orientation. The results showed that vertical finger orientation had the higher mean of modulus of rupture and the Modulus of Elasticity *i.e.* 24.49 MPa (28.91 MPa) and 8,814 MPa (11,668 MPa), respectively. However, in control, specimen characteristics did not meet the minimum strength.

Thulasidas and Bhat (2012) observed the teak wood grown in home-garden forestry for the mechanical and anatomical characteristics which influences the timber strength in comparison to that of a typical forest plantation in Kerala. With respect to wet, dry and plantation sites, non-significant differences were noticed in Modulus of Elasticity and modulus of rupture and the values were moderate compared with the standard teak. Dry site home-garden teak showed higher compressive strength parallel to grain (60.6 N/mm^2) and differed significantly between wet and plantation sites. The higher compressive strength value was correlated with higher air-dry density (691 kg/m^3) observed, coupled with thick fibre wall and smaller fibre lumen as depicted by anatomical studies. The results of the study revealed that the wood quality attributes such as density and strength did not affect farmer's choice to fell homestead teak at short-rotation of 35-years. Verma *et al*. (2012) analysed the tensile characteristics of bamboo laminae, made from bamboo slivers, selected from different regions of bamboo culms (*Dendrocalamus strictus*) and observed that these characteristics increased from inner to outer region for any cross section and bottom to top. They also noticed that fibre strength increased and matrix strength decreased from bottom to top whereas, fibres modulus decreased and matrix modulus increased from bottom to top of bamboo culms. Gutu (2013) noticed that the mechanical characteristics of the bamboo in Zimbabwe and observed that the strength characteristics of bamboo were higher than most of the soft and hard woods. He also observed that solid and hollow bamboo can equally be utilized for both furniture products and construction work.

Elzaki and Khider (2013) evaluated the strength characteristics of *Ailanthus excelsa* from Western Sudan with the same wood species from India which includes static bending tests, impact bending, compression strength parallel to grain, maximum crushing strength as well as shear stress were studied. The results obtained has shown that the average value for the basic density (316.0 kg/m^3), MOR (468.0 kPa/cm^2), compressive strength of the Sudanese Ailanth was lower than that of the Indian for basic density (361.0 kg /m^3) and MOR (543.0 kPa /cm^2), respectively. Due to the obtained results, the wood of *Ailanthus excelsa* could be classified as a low-density hardwood which cannot be used for structural purposes but can be used for light industries such as matchwood, veneer, and boat building. Jamala *et al.* (2013) showed a significant (P=.05) variation in wood density (*Afzelia africana*>*Celtis mildbraedii*>*Meliceae excelsa* >*Khaya ivorensis*>*Triplochiton scleroxylon*).The MOR (N/mm^2) and MOE (N/mm^2) of these wood species observed that *Celtis mildbraedii* and *Afzelia africana* noticed the highest values (149.94/7088 and 136.71/6313), *Khayaivorensis*, *Meliceae excelsa* and *Triplochiton scleroxylon* observed a relatively lower values. He also noticed that the mechanical characteristics of (MOR and MOE) selected wood species in tropical rainforest ecosystem and the results provided quantitative information on the mechanical characteristics of selected wood species which can be used in determining the application of wood for either heavy and for building, construction or for other purposes such as the manufacture of furniture.

Romagnoli and Spina (2013) noticed that the ring shake is a defect that strongly affects chestnut (*Castanea sativa* Mill.) wood use and its occurrence is mainly related to mechanical stress within a tree. The results revealed that trees with ring shake had minimum mechanical strength and shrinkages than healthy ones and that the physico-mechanical parameters might be used to predict ring shake occurrence in a specific geographic area and there was variation between the ring shaked and healthy portions of a disk inside the same tree. Shukor *et al*. (2013) observed the mechanical characteristics of multiple leadered *Acacia crassicarpa.* They also showed that ML2 (multiple leaders) trees gave better physical and mechanical characteristics compared to ML3. In particular, the number of leaders affect the strength and stiffness but not in terms of provenances and they stated that trees with many stems tend to have weaker physical strength when compared to those with a few stems. Skarvelis and Mantanis (2013) noticed that the characteristics of beech wood (*Fagus sylvatica* L.), one of the most important hardwood species, harvested in the Greek public forests. With regard to the mechanical characteristics, the average values for static bending, Janka hardness and compression parallel to the grain, compression perpendicular to the grain, shear, impact bending and cleavage of beech wood were noticed to be 105.49, 48.54, 55.43, 11.96, 14.85, 784.35 and 26.45 N mm^{-2} respectively.

Alam *et al.* (2014) observed the effect of waterlogged condition on wood characteristics of *Acacia nilotica*. The MOR of the wood of waterlogged tree and non-waterlogged tree was 117 N/mm^2 and 127 N/mm^2 respectively. The MOE of the wood of waterlogged tree and non-waterlogged tree was 1880 and 1950 N/mm^2 respectively and the variation in these characteristics of *A. nilotica* wood grown in different conditions, will be helpful in deciding its uses for suitable purposes. Anoop *et al.* (2014) observed the *Swietenia macrophylla* introduced at Olavakkode research range at Dhoni, Palakkad in Kerala, south India. Results indicated that the *S. macrophylla* logs had a volume of 0.17 m^3 and bark thickness as 2.9± 2.1 mm. Heartwood percentage was 89 and the logs had sawn wood recovery of 54 per cent. Most of the wood physical and anatomical characteristics varied along the radial directions from pith to periphery. Physico-mechanical characteristics were correlated with anatomical characteristics and most of the wood quality parameters were comparable to teak.

Heena (2014) observed significant variation between mechanical characteristics of different Willow clones growing at two sites. The maximum tensile strength was recorded in clone J-795 (0.073 kN/mm^2) and maximum bending strength (0.006 kN/mm^2) was noticed in clones SE-63-016 and V-99. The tensile and bending strength determined for Teak wood samples was 0.089 kN/mm^2 and 0.031 kN/mm^2, respectively. The maximum compressive strength parallel to grain (0.044 kN/mm^2) was observed in *Salix babylonica* and maximum compressive strength perpendicular to grain (0.007 kN/mm^2) was noticed in clone MB-368. The compressive strength parallel to grain and perpendicular to grain was estimated to be 0.074 kN/mm^2 and 0.019 kN/mm^2, respectively in standard Teak wood samples. Mechanical characteristics of Willow clones were compared with Standard Teak wood samples and observed that the wood samples of Teak were superior to all the Willow clones.

Huda *et al*. (2014) observed the clonal variation of selected mechanical characteristics of seven hybrid poplar clones grown at three sites in southern Quebec, Canada. They noticed that hybrid poplar wood revealed significant interclonal variation in wood characteristics, especially flexural modulus of rupture and ultimate crushing strength. They also noticed that high heritability values of these characteristics were under moderate to high genetic control and the genetic gain for these characteristics ranged from 2.0 to 13.5 per cent. Kamala *et al.* (2014) observed that mechanical characteristics of small clear wood specimens of *Pinus patula* planted in Malawi in order to provide a basis for its utilization and noticed the average air-dry density was 0.54 g/cm^3. The maximum MOE and MOR of 11.90 GPa and 111.47 MPa respectively was noticed for *Pinus patula.* Nordahlia *et al.* (2014) analysed wood from seedling and rooted-cutting of sentang (*Azadirachta excelsa*) trees and showed no significant difference in modulus of rupture. With respect to wood from seedling trees, the wood from rooted cutting trees observed higher Modulus of Elasticity. On the other hand, compression and shear parallel to the grain were significantly higher in wood planted from seedling compared with wood from rooted-cutting trees and mechanical characteristics at the bottom portion towards the top increased irrespective of the planting technique.

Okoh (2014) observed the physical (oven dry density) and mechanical characteristics (modulus of rupture, Modulus of Elasticity, compression parallel to the grain) of four tropical hardwood species (*Terminalia superba* (Ofram) and *Terminalia ivorensis* (Emere), as currently threatened timber species and *Quassia undulata* (Hotrohotro) and *Recinodendron heudelotii* (Wama) as lesser used timber species to measure and compare their timber characteristics as potential substitutes. The study noticed that, the densities, compression parallel to grain, modulus of rapture and Modulus of Elasticity of Ofram and Hortrohotro were not significant, but that of Emere and Wama were significant. The Modulus of Elasticity of Emere was, however, not significant and based on these findings Hortrohotro could be substituted for Ofram and Emere with Wama. Saravanan *et al.* (2014) observed studies on mechanical characteristics at Forest College and Research Institute, Mettupalayam, Tamil Nadu, India and they used different age gradation *viz.*, three, four and five year of *Melia dubia* wood samples for study. The maximum value for the parameters like static bending strength, modulus of rupture, Modulus of Elasticity, compression strength parallel to grain, compression strength perpendicular to grain, hardness, shearing stress parallel to grain, tensile stress parallel and perpendicular to grain, nail-holding power, screw-holding power, brittleness, and cleavage strength parallel to grain was observed for age gradations of five year old *M. dubia* registered. The studies observed that the five-year-old wood was suitable as a raw material for plywood, pencil, packing cases, and light furniture industry and he also observed that the mechanical characteristics increase with maturity of wood. The values of static bending strength recorded were 616.30, 524.30 and 312.80 kg/cm^2 for fifth, fourth- and third-year *Melia dubia* woods respectively and the mean MOR value obtained in the study were 492.60 to 851.90 kg/cm^2 for three, four and five-year-old woods respectively. The mean values for MOE of third, fourth- and fifth-year *Melia dubia* woods were 52872.20, 63212.50 and 68384.50 kg /cm^2 respectively and the mean values compression parallel to grain of selected wood of *Melia dubia* were observed to be 241.00, 250.60 and 283.30 kg cm^{-2} for age of three, four- and five-year trees respectively. The mean values for compression strength perpendicular to grain of wood were ranged from 31.80 kg cm^{-2} (third year) to 104.20 kg cm^{-2} (fifth year) respectively. The tensile stress of *Melia dubia* also reported an increase in tree age *Melia dubia.*

Ataguba *et al.* (2015) carried out studies on mechanical characteristics of *Gmelina arborea* and observed that the estimated values for compression parallel to grain as 7.4 N/mm^2, compression perpendicular to grain 2.5 N/mm^2, tensile strength 6.5 N/mm^2 and 7993.3 N/mm^2 for Modulus of Elasticity. They concluded that mechanical characteristics can be enhanced with adequate seasoning, if these timbers are for structural purposes based on these results. Riyaphan *et al*. (2015) observed variability in mechanical characteristics of *Hevea brasiliensis* (para rubber) trees. The results revealed that the trees were significantly different for tensile stress perpendicular to grain but the MOE, compressive stress parallel and perpendicular to the grain, shearing stress parallel to the grain, hardness, and cleavage were not significantly different. The maximum values for MOR and MOE indicated a greater strength and stiffness respectively and they finally stated that the rubber wood could be a useful material for building construction due to the strength characteristics.

Ruwanpathirana *et al*. (2015) determined the strength parameters of non-class timber species and the parameters at serviceability limit, mainly compressive strength at parallel to grains varies 13 MPa - 45 MPa and compressive strength perpendicular to grains varies 3MPa – 22 MPa in most of the non-class timber species. They also classified the timber according to available strength classes and proposed suitable applications for each type. Zahabu *et al.* (2015) evaluated the effects of spacing on growth, yield, and wood characteristics of teak planted at square spacing regimes of 2m, 3 m, and 4m at Longuza Forest Plantation, Tanzania. It was observed that there was no effect of spacing on density, however, basic density heartwood proportion increased with increase in spacing. All the studied wood characteristics (modulus of rupture, Modulus of Elasticity, compression strength tangential to grain, and shear tangential to the grain) except cleavage tangential to grain were not significantly affected by increasing spacing. It was advised to use the spacing of 3m × 3m, but if thinning could be done before onset of competition at 5 years, the currently used spacing of 2.5m × 2.5m could still be used and use of a spacing of 4m × 4m could give at least 50 per cent heartwood at shorter rotation age of 30 years. In terms of mechanical characteristics, Machado and Cruz (2005) observed a clear increase in MOR and MOE throughout the radial direction, from the pith to the bark. The mechanical characteristics significant variation within the three anatomical directions: Longitudinal, radial and tangential. They also showed variation between individual species, from tree to tree and within the tree. The study revealed that all mechanical characteristics except cleavage tangential to grain were not significantly affected by planting spacing and was inherent in nature depending upon their cellular structure.

Kumar (2016) observed the variation in strength characteristics of *Pinus roxburghii* in his research and noticed the mean tensile strength for Chirpine wood selected from different sites of Himachal Pradesh ranging from 0.022 kN/mm^2 to 0.043 kN/mm^2, bending strength from 0.0033 kN/mm^2 to 0.0089 kN/mm^2 and compression parallel and perpendicular to grain from 0.034 kN/mm^2 to 0.057 kN/mm^2 and 0.0062 kN/mm^2 to 0.0180 kN/mm^2 respectively. Mahmood *et al*. (2016) evaluated the mechanical characteristics of salt tolerant tree species viz. *Eucalyptus camaldulensis, Acacia nilotica, Prosopis juliflora and Tamarix aphylla* with *Dalbergia sissoo.* The results observed maximum static bending strength and Modulus of Elasticity in *Acacia nilotica* while minimum in *Tamarix aphylla* whereas the crushing strength parallel to grain was observed maximum in *P. juliflora* (610 kg cm^{-2}) and minimum in *A. nilotica* (321 kg cm^{-2}). They finally observed that all tested tree species had strength characteristics of comparable with *Dalbergia sissoo* wood and thus have good utilization potential for different wood products.

San *et al*. (2016) analysed the mechanical characteristics (bending, hardness and compression parallel to the grain) of *Paulownia* hybrid. After the bending test, the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) were determined using the center point loading formula. The results noticed maximum strength to weight ratio for green *Paulownia* with the value of 0.137 for MOR and 17.14 for MOE. From the study, they finally stated that *Paulownia* timber could be utilized as good material for furniture. Zziwa *et al*. (2016) analysed mechanical characteristics of *Mangifera* *indica* and noticed that mean basic density of *Mangifera indica* ranged from 534 kg/m^3 to 585kg/m^3 and the mean MOE and MOR of *Mangifera indica* ranged from 5,617.0 N/mm^2 to 8,027.8N/mm^2 and 46.6 N/mm^2 to 74.2 N/mm^2 respectively. The species found suitable as a light construction timber for furniture production and they also stated that during utilization of the tree species preference should be given to the middle portion of the entire tree stem on account of the better strength characteristics. These characteristics, however, vary not only within the species but also with moisture content, temperature and defects in the wood subjected to various forces and about these mechanical characteristics is obtained through experimentation or by means of special testing apparatus in the laboratory.

Sunny *et al.* (2019) observed the wood characteristics of Dalbergia *sissoo* procured from different market sites of Himachal Pradesh. The maximum bending strength was recorded in Baroh and Sundernagar site (0.006 kN/mm^2) and maximum tensile strength (0.094 kN/mm^2) was noticed in the wood samples from Baroh site. The maximum compressive strength parallel to grain (0.069 kN/mm^2) was determined for Kangu site and maximum compressive strength perpendicular to grain (0.038 kN/mm^2) was recorded for Baroh site. The maximum Modulus of Elasticity parallel to grain (0.231 kN/mm^2) was observed in Ghumarwin and maximum Modulus of Elasticity perpendicular to grain (1.653 kN/mm^2) was recorded for wood samples from Galore site. Higher Modulus of Elasticity due to tension and bending are in the wood samples of Baroh (2.876 kN/mm^2) and Kangu (10.369 kN/mm^2) sites respectively. The maximum bending modulus of rupture was noticed in the wood samples from the sites of Sundernagar (0.116 kN/mm^2) and for Teak was observed to be 0.323 kN/mm^2. The maximum elongation for shisham wood samples for bending was noticed for Nalagarh site (0.039 mm) and for tension in the site of Sarahan (0.033 mm).

3. MATERIALS AND METHODS

The present study was carried out to investigate the zonal variations in wood properties of Jack trees *(Artocarpus heterophyllus* Lam.) grown in three different altitudinal zones of Thrissur district, Kerala. The samples were collected from the local markets based on three different girth classes *i.e.* 30 cm-60 cm, 60 cm-90 cm and 90 cm-120 cm. Three samples of each girth classes from different sites were collected which constitute 27 wood samples (Plate 2). Wood property studies were conducted in the department of Forest Products and Utilization, College of Forestry, Kerala Agricultural University, Vellanikkara.

Species under the study

Species: *Artocarpus heterophyllus*

Family: Moraceae

Order: Rosales

3.1 MATERIALS

3.1.1 The Study Area and Geographical Location

The experimental materials for the study consisted of 27 *Artocarpus heterophyllus* wood collected from different local market sites of Thrissur district considering the girth classes (Plate 1).

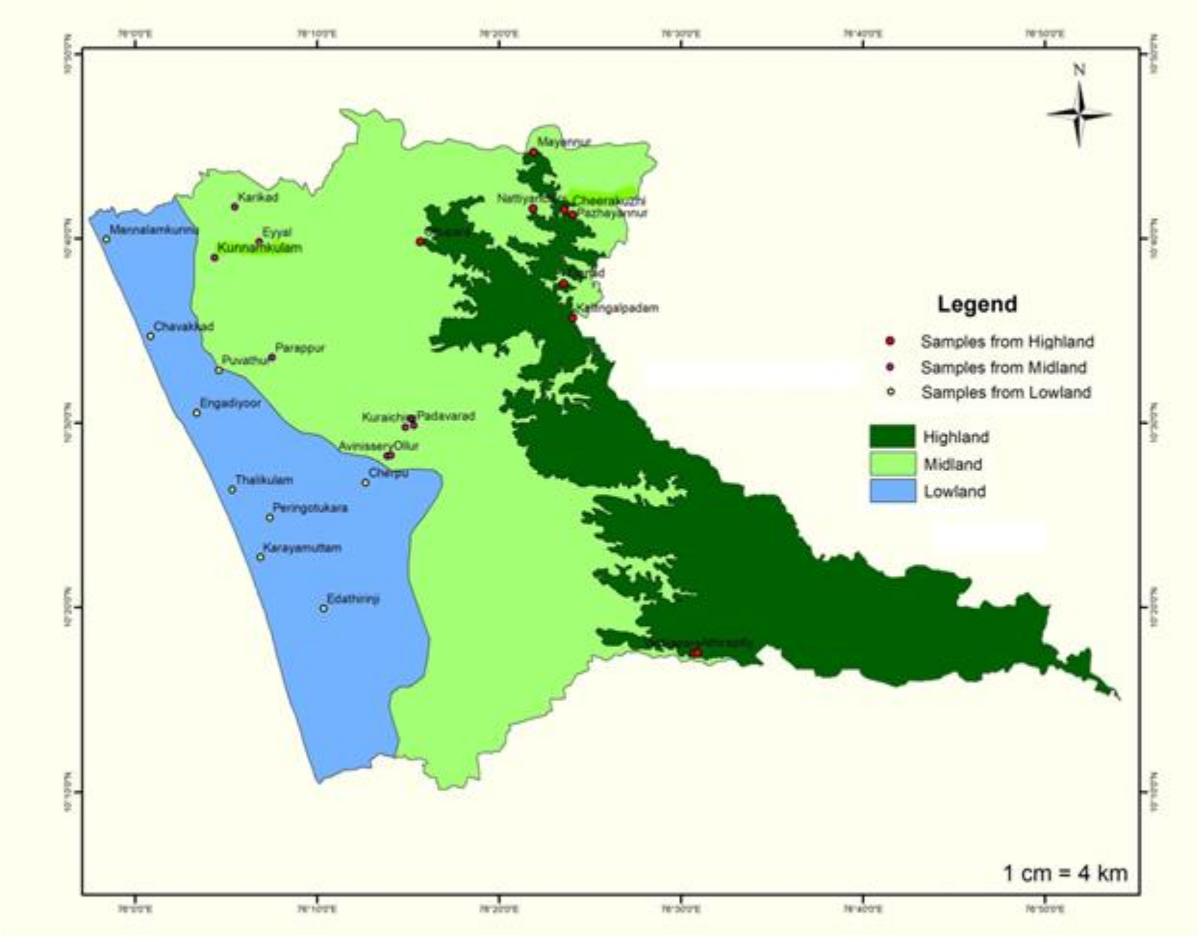


Plate 1: Different sites of *Artocarpus heterophyllus* wood procurement from Thrissur district, Kerala, India

The present work was carried out in Thrissur district, Kerala (10°31’49.2420” N, 76°12’53.0244” E)

Table 1: Details of sites and coordinates for Jack wood procurement

Zones	Girth classes	Sites	Latitude	Longitude
Lowland	30cm-60cm	Puvathur	10^{o}32’51.5” N	76^{o}04’35.9” E
		Thalikulam	10^{o}26’23.1” N	76^{o}05’20.4” E
		Peringotukara	10^{o}24’52.5” N	76^{o} 07’23.9” E
	60cm-90cm	Engadiyoor	10^{o}30’33.4” N	76^{o} 03’23.0” E
		Karayamuttam	10^{o}22’42.8” N	76^{o} 06’52.2” E
		Edathirinji	10^{o}19’56.4” N	76^{o}10’21.7” E
	90cm-120cm	Parappur	10^{o}33’32.9” N	76^{o}07’31.7” E
		Mannalamkunnu	10^{o}39’57.0” N	75^{o} 58’25.8” E
		Chavakkad	10^{o}34’50.6” N	76^{o} 01’20.0” E
Midland	30cm-60cm	Kunnankulam	10^{o}38’57.8” N	76^{o}04’22.0” E
		Avinissery	10^{o}28’12.6” N	76^{o} 13’51.3” E
		Cherpu	10^{o}26’45.8” N	76^{o} 12’39.9” E
	60cm-90cm	Padavarad	10^{o}29’51.3” N	76^{o} 15’19.1” E
		Kuttanellur	10^{o}30’21.6” N	76^{o} 15’06.4” E
		Ollur	10^{o}28’14.4” N	76^{o} 14’02.4” E
	90cm-120cm	Eyyal	10^{o}39’49.0” N	76^{o} 06’49.5” E
		Karikad	10^{o}41’42.9” N	76^{o}05’28.6” E
		Kuriachira	10^{o}29’46.6” N	76^{o} 14’50.6” E
Highland	30cm-60cm	Pazhayannur	10^{o}41’52.7” N	76^{o}25’30.0” E
		Kallingalpadam	10^{o}35’28.2” N	76^{o}25’12.9” E
		Vettilapara	10^{o}17’29.2” N	76^{o}30’41.8” E
		Cheerakuzhi	10^{o} 42’14.4” N	76^{o}25’34.9” E

	60cm-90cm	Ottupara	10 ^{o}40’25.5” N	76^{o}15’23.9” E
		Athirapilly	10 ^{o}17’31.7” N	76^{o}30’53.6” E
	90cm-120cm	Mayannur	10 ^{o}45’15.2” N	76^{o}22’34.8” E
		Elanad	10 ^{o}37’37.9” N	76^{o}23’38.0” E
		Nattiyanchira	10 ^{o}41’36.1” N	76^{o}21’57.9” E

3.2. METHODS

The experimental materials were collected from three altitudinal zones (9 individual trees each from lowland, midland and highland) which also include trees from girth classes 30 cm-60 cm, 60 cm-90 cm and 90 cm -120 cm (Plate 3). The classification zones were done mainly based on the altitude of each of the localities. The area with an altitudinal range 0-7.5 meter (m) above mean sea level is classified as lowland, similarly midland and highland regions with 7.5 m-75 m and > 75 m altitudes respectively (ENVIS, 2017). Wood samples of three trees were collected from each girth classes (Plate 3). For comparing the wood properties from zones of Thrissur district following stratified random sampling technique.

3.3 RECORDING OF DATA

3.3.1 PHYSICAL PROPERTIES

Wood specimens of size 2 cm ×2 cm ×2.5 cm was made out from each sample assessing wood basic density, moisture content and heartwood colour (ISI, 1986).

i) Basic Density and Specific gravity

The basic density of wood was determined by using immersion method. This is the ratio between the dry weights of wood and the green volume of the same wood. Wood specimens of size 2 cm ×2 cm ×2.5 cm was made out from the wood samples collected from the zones. Green volume of the sample was estimated using the immersion method. A container capable of holding the sample was filled with water and placed on a digital balance of precision 0.0001 g.

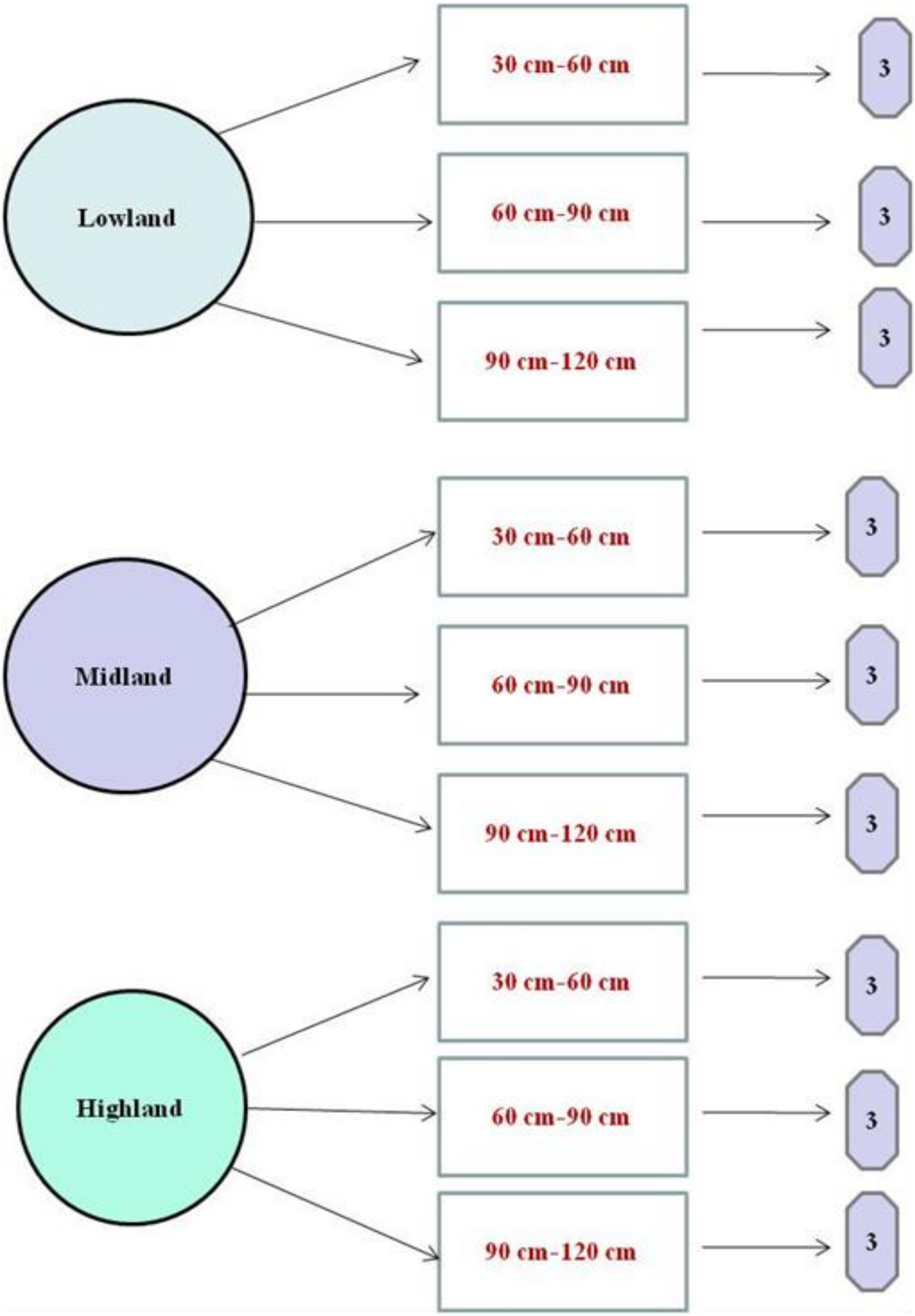


Plate 2: Method of procurement of *Artocarpus heterophyllus* wood samples

The samples were then carefully sunk in the water, such that the surface water should coincide with the surface of wood. The container should not be completely filled with water. The samples should not contact the sides or bottom of the container, and it should be forced under water with a thin needle. Samples were then oven dried at $103 \pm 2^{o}C$ until weight became constant for the determination of oven dry weight using a precision electronic balance (Shimadzu AUY 220) and were weighed correct to 0.001 g (Plate 4). Basic density (standard specific gravity) of wood specimens was calculated and by dividing it with density of water we get specific gravity of wood.

$$\text{Basic density (kg/ m}^3\text{)} = \frac{\text{Oven dry weight}}{\text{Green volume}}$$

$$\text{Specific gravity} = \frac{\text{Basic density of wood obtained}}{\text{Density of water}}$$

ii) Moisture Content

In order to determine moisture content, the samples were weighed to an accuracy of 0.001 g in a weighing balance (Shimadzu AUY 220) and then dried in a hot air oven at a temperature of 103±2°C till a constant weight. The final weight has been taken as oven dry weight. The moisture per cent of the samples was calculated by using the formula given by Desch and Dinwoodie (1996).

$$\text{Moisture content (\%)} = \frac{Mi - Mo}{Mo} \times 100$$

Where,

M_i = Initial weight of sample (g)

M_o = Oven dried weight of sample (g)

iii) Colour

Colour of the heartwood has been investigated by CIE Lab colour system. Heartwood colour variation was quantitatively measured in reflectance mode as

Plate 3: Collection of *Artocarpus heterophyllus* wood samples from the local market sites in three different zones

CIELAB colour co-ordinates (10° standard observer, D65 standard illuminant) using Hunter Lab Scan XE colorimeter (IWST, Bangalore) (Plate 5). CIELAB L*, a*, b* parameters were measured on each specimen and average value was calculated. In the CIELAB system, the L *axis represents lightness from black to white (L*=0, the darkest black and L*=100, the brightest white); a* and b* are the chromaticity coordinates (+a* is for red, -a* for green; +b* for yellow, -b* for blue).

iv) Texture

Wood texture describes the relative size as well as the amount of variation in size of the wood cells. It depends upon the size of the cells and its distribution and proportion of the various types of cells. Texture of *Tectona grandis* ranges from medium to coarse and was determined based upon the range of tangential diameters of vessels under four main classes (Peng *et al.*, 1988) as given below:

Texture			Mean tangential diameter of vessels
(a)	Very fine	:	<100 µm
(b)	Fine	:	100-200 µm
(c)	Medium	:	200-300 µm
(d)	Coarse	:	>300 µm

v) Volumetric Shrinkage

To estimate volumetric shrinkage, the specimen was initially weighed in the green condition with a precision of 0.00l g and the volume was determined by immersion method. A suitable vessel, half filled with water, was kept on the pan of a weighing balance. The specimen was then completely dipped in water by means of a needle and weighed again. Care was taken such that no air bubble stick to the specimen and that the specimen was not touching the side of the vessel. The difference between the two readings is the green volume of the specimen. The specimen was then kept in a hot air oven at 103±2°C until constant weight is attained. After oven-drying, the specimen was again weighed and oven dried volume was determined by immersion as before. The percentage volumetric shrinkage was given by the formula,

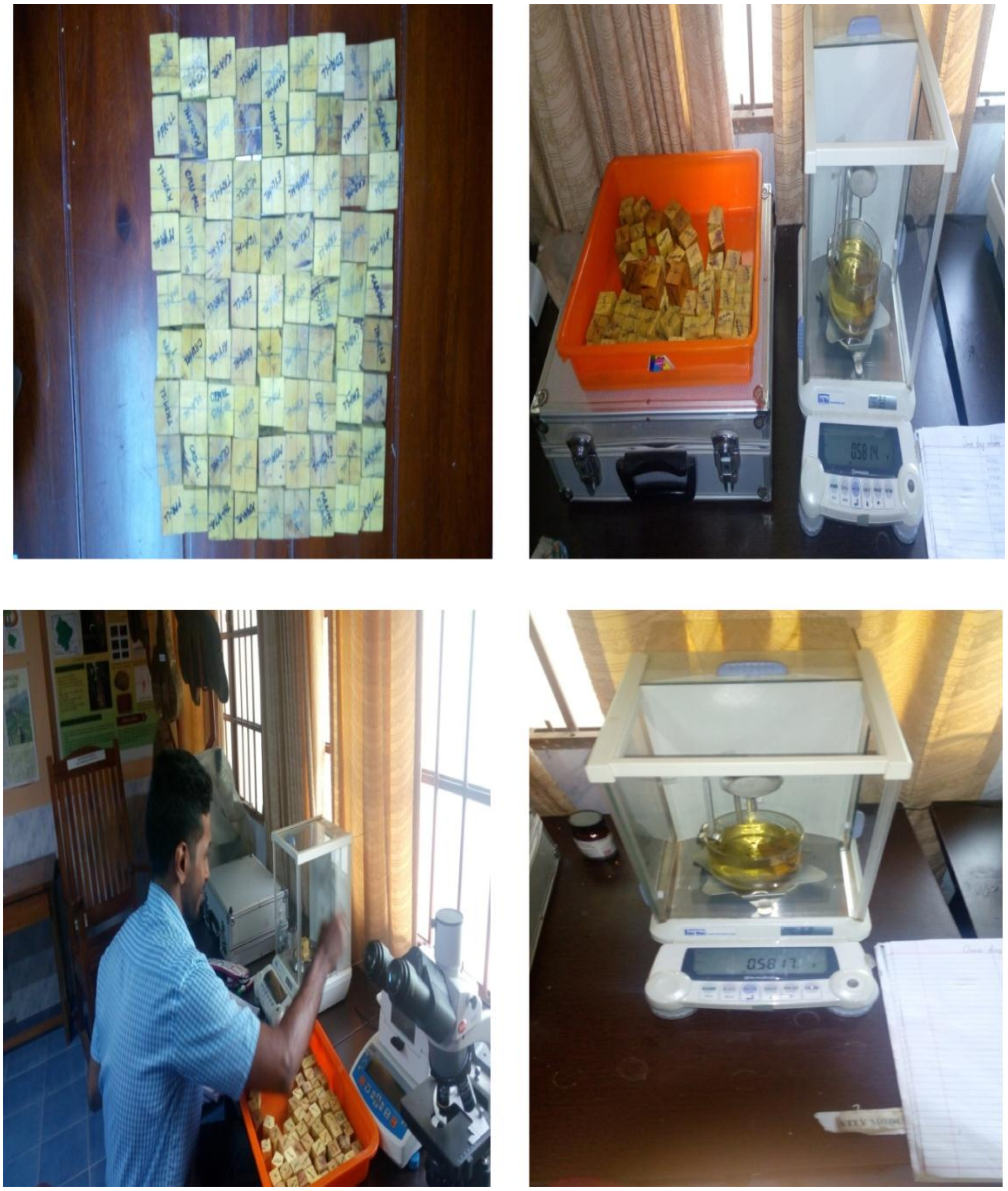


Plate 4: Specific gravity determination of *Artocarpus heterophyllus* wood samples

$$\text{Volumetric shrinkage (\%)} = \frac{\text{Green volume} - \text{Oven dry volume}}{\text{Green volume}} \times 100$$

vi) Dimensional shrinkage

Dimensional shrinkage includes tangential shrinkage and radial shrinkage. To estimate dimensional shrinkage, the length of the specimen was measured correct to 0.01 cm by means of a digital vernier caliper. Centre and corners of specimen were marked to make subsequent measurements. The specimens were dried in an oven at 103±2^{o}C until a constant weight is attained. The specimens were then measured finally. The percentage dimensional shrinkage was given by the formula,

$$\text{Dimensional shrinkage (\%)} = \frac{\text{Initial length} - \text{Oven dry length}}{\text{Initial length}} \times 100$$

3.3.2 ANATOMICAL PROPERTIES

i) Microtomy

Wood specimens of size 1 cm^3 were chiseled out from each sample and used for anatomical studies. The specimens were then softened by keeping in water bath (Rotex water bath) at 100^{o}C depending on the nature of specimen. Transverse section (TS), tangential longitudinal section (TLS) and radial (RLS) sections of 10-15 µm thickness were prepared using a Leica sliding wood microtome (Leica SM 2000R) (Plate 6a). The sections were stained using saffranin and later washed through a series of alcohol solutions at different concentrations (70 %, 90 % and 95 %) to ensure complete dehydration (Plate 6b). They were subsequently dipped in acetone followed by xylene and finally mounted in DPX mountant to prepare permanent slides (Johansen, 1940).

ii) Image analysis

Permanent slides were examined using an image analyser (CatCam 500E series) which is provided with a microscope (Motic BA 210), digital camera and a personal computer (Plate 6d). Images of the sections were captured and then measurements including length, diameter, thickness and proportions of fibre, vessel and rays were made using the software Catymage.

Plate 5: Color determination of *Artocarpus heterophyllus* wood samples by using Hunter Lab Scan XE colorimeter (IWST, Bangalore, Karnataka)

3.3.2.1 Vessel morphology

i) Vessel diameter

Vessel diameter was measured from the image of cross section taken in image analyser. Images were taken in 10X. For measuring vessel diameter, two readings were taken using line tool and its average was noted as the vessel diameter. Vessel diameter was expressed in micrometers (µm) (Plate 7b).

ii) Vessel area

Vessel area was taken from the image taken in an image analyser. Observations were taken using an area tool. It was expressed in micrometer square (µm^2). The images were taken in 10X.

iii) Vessel length

Vessel length obtained from maceration was observed under an image analyser. Observations were taken using an line tool. It was expressed in micrometer square (µm^2). The images were taken in 10X.

iv) Vessel frequency

Vessel frequency was measured from the images taken in 4X from five replications of the sample using the following formula. The mean of the values of replications were taken as vessel frequency.

$$\text{Vessel frequency} = \frac{\text{Number of vessels}}{\text{Area in sq.microns}} \times 10^6$$

Plate 6: (a) Leica SM 2000R sliding microtome, (b) Chemicals for slide preparation, (c) Sections prepared for slide preparation, (d) Prepared slides, (e) PC with Image analyser (CatCam 500E series camera using Catymage software.

3.3.2.1.1 Ecoanatomical properties

The ecoanatomical properties are being calculated by using the formulae by Carlquist (1977).

$$\text{Vulnerability index} = \frac{\text{Mean vessel member diameter}}{\text{Mean vessel frequency}}$$

Vessel mesomorphy= Vulnerability index× Mean vessel length

3.3.2.2 Ray morphology

i) Ray height

From the tangential section of six-month-old stem, ray height was measured with the help of analysis software, Catymage and was expressed in micrometers (µm). Mean value was expressed as ray height (Plate 7e).

v) Ray width

Ray width was measured using the line tool of analysis software, Catymage. Mean value of observations was expressed as Ray width in micrometers (µm).

vi) Ray frequency

Ray frequency was measured from the images taken in 4X from five replications of the sample by using the line tool in image analyzing software i.e. number of rays touching per mm of line.

3.3.2.3 Fibre morphology

i) Maceration

Six-month-old stem samples of two varieties from each location were macerated for measuring fibre characteristics such as fibre length, fibre width, lumen diameter and wall thickness. Maceration of the sample was done by Jeffrey's method (Jeffry, 1917), using Jeffry's solution. Jeffrey's solution was prepared by mixing

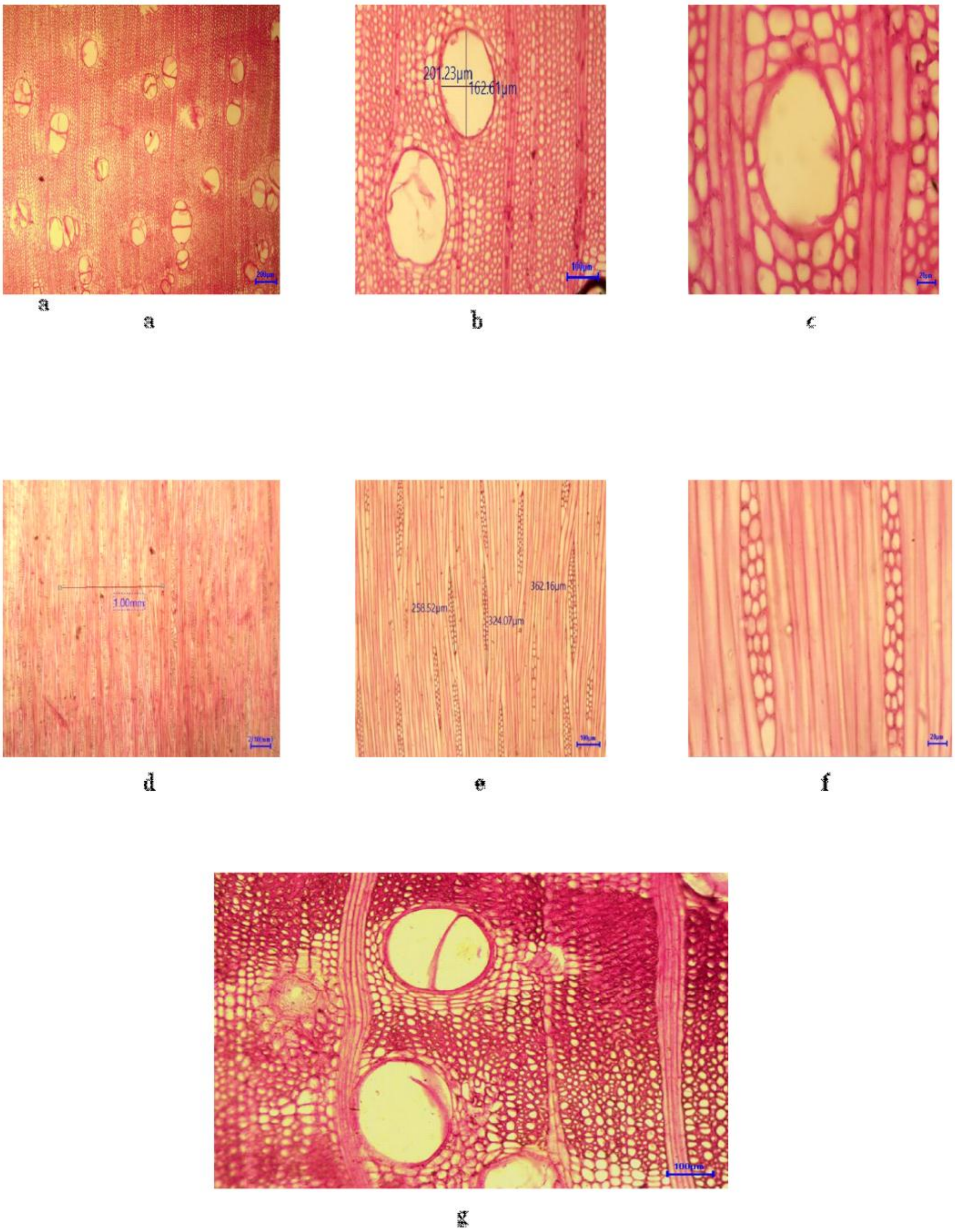


Plate 7: (a) Transverse section 4X, (b) Transverse section 10X, (c) Transverse section 40 X, (d) Tangential section 4X, (e) Tangential section 10X, (f) Tangential section 40X, (g) Aliform parenchyma 10X

equal volumes of 10 per cent potassium dichromate and 10 per cent Nitric acid. Chips of stem shavings were taken from the sample material. These chips were boiled in the maceration fluid for 15-20 minutes so that individual fibres were separated (Plate 8a). Then these test tubes were kept for 5-10 minutes so that the fibres settled at the bottom. The solution was discarded and the resultant material was thoroughly washed in distilled water until traces of acid were removed. The samples were stained using safranine and mounted on a temporary slide using glycerine as the mountant. Temporary slides were observed under the microscope (Plate 8b, 8c, 8d, 8e). Measurement of fibre dimension was carried out using an image analyser (Catymage and CatCam 500E series).

ii) Fibre length

Fibres obtained from maceration were observed under an image analyser. The line tool was used to measure the fibre length. The images were taken in 10X. It was measured in micrometers (µm).

iii) Fibre width

Fibre width was measured from the images of sample taken in 40X using an image analyser. It was measured in micrometers (µm)

iv) Lumen diameter

Lumen diameter of a fibre was measured from the images taken in 40X using an image analyser in micrometers (µm)

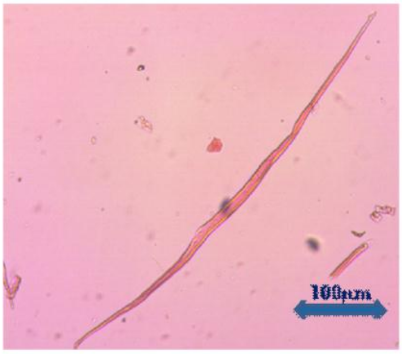
v) Wall thickness

Wall thickness was measured by using the following formula

$$\text{Wall thickness} = \frac{\text{Fibre diameter} - \text{lumen diameter}}{2}$$

a

b



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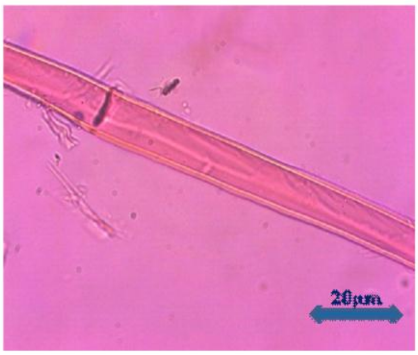

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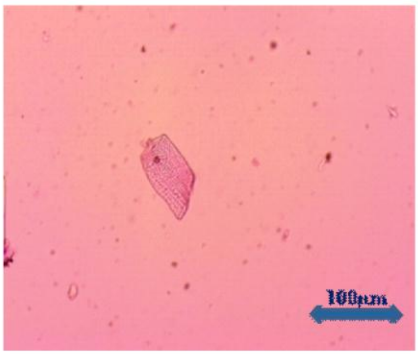

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Plate 8: (a) Determination of fibre and vessel parameter by using Maceration method, (b) Fibre 4X, (c) Fibre 10X, (d) Fibre 40X, (e) Vessel 10X

vi) Runkel ratio

Runkel ratio was measured by using the following formula

$$\text{Runkel ratio} = \frac{2 \times \text{Wall thickness}}{\text{Lumen diameter}}$$

vii) Slenderness ratio

Slenderness ratio was measured by using the following formula

$$\text{Slenderness ratio} = \frac{2 \times \text{Fibre length}}{\text{Fibre diameter}}$$

viii) Shape factor

Shape factor was measured by using the following formula

$$\text{Shape factor} = \frac{(\text{Fibre diameter})^2 - (\text{Lumen diameter})^2}{(\text{Fibre diameter})^2 - (\text{Lumen diameter})^2}$$

3.3.2.3 Tissue proportion

Tissue proportion is done by using the image analysis software in which a line of particular length is drawn in the anatomical section obtained by using the line tool. The respective number of cells whether it's the vessels, rays, parenchyma and fibres are being counted and the individual percent of each type of cells are being calculated,

$$\text{Vessel (\%)} = \frac{\text{Number of vessels}}{\text{Total number of all the cells}} \times 100$$

$$\text{Ray (\%)} = \frac{\text{Number of rays}}{\text{Total number of all the cells}} \times 100$$

$$\text{Parenchyma (\%)} = \frac{\text{Number of parenchyma}}{\text{Total number of cells}} \times 100$$

$$\text{Fibres (\%)} = \frac{\text{Number of fibres}}{\text{Total number of cells}} \times 100$$

3.3.3 CHEMICAL PROPERTIES OF *Artocarpus heterophyllus* WOOD

The proximate chemical analysis was carried out by employing TAPPI (Technical Association of the Pulp and Paper Industry) and by Sadasivam and Manickam (1992) standard methods.

3.3.3.1 Determination of water-soluble extractives

The water-soluble extractives were determined by employing following methods:

i) Cold water solubility (T1m-59-Anonymous, 1959a)

Two grams of oven dry wood meal was weighed and transferred into a conical flask containing 300 ml of distilled water. The mixture was digested at room temperature with frequent stirring for 48 hours. Then material was filtered through IG-1 crucible and washed thoroughly with cold 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 (Plate 9c).

ii) Hot water solubility (T1m-59-Anonymous, 1959a)

Two grams of oven dry wood meal was taken in a flask having 100 ml of double distilled water filtered with reflux condenser. It was digested on boiling water bath for 3 hours. Then contents were filtered through IG-1 crucible and residue was dried in an 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 (Plate 9d).

3.3.3.2 Determination of chemical soluble extractives

i) NaOH soluble extractives (T212m-02-Anonymous, 1959b)

Two grams of oven dry wood meal was weighed and transferred into a conical flask of 250 ml. Then 100 ml of 1 percent NaOH solution was added to it and stirring was done with a glass rod. The flask was covered with a watch glass and place in a water bath maintained at 97 to 100°C for one hour. Then, contents were filtered through Wattman filter paper. The sample was dried in an oven at 105±2˚C to a constant weight. The solubility was determined by calculating the loss in weight of the sample taken and expressed as percentage.

ii) Alcohol-benzene extractives (T6m-59-Anonymous, 1959b)

Ten grams oven dry powdered wood sample 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 six hours. Then, porous thimble was taken out and allowed to dry in open air and finally in an oven at 105±2˚C till constant weight. The alcohol-benzene solubility was determined by calculating the loss in weight of the sample taken and expressed in percentage.

iii) Determination of Holocellulose (T9m-59-Anonymous, 1959)

Five grams 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. Then 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. Then contents were filtered through IG-2 crucible, washed with water and finally with acetone. The sample was dried in an oven at 105±2˚C to a constant weight. The percent holocellulose content was calculated on the basis of the oven dry weight (Plate 9g).

iv) Determination of Klason-lignin content (T12m-59-Anonymous, 1959c)

Two grams oven dry 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, washed with hot distilled water and dried in an oven at 105±2˚C till constant weight and expressed in percentage on oven dry weight basis (Plate 9f).

Plate 9: (a) Basic analytical mill- IKA A11, (b) Test sieves for saw dust, (c) Cold and Hot water solubility, (e) Soxhlet apparatus, (f) Klason lignin content, (g) Holocellulose content

v) Determination of Cellulose

Cellulose content of the wood was estimated following Sadasivam and Manickam (1992). For this finely powdered pre extracted saw dust were taken. After taking the pre extracted saw dust, prepare Acetic/Nitric Reagent by mixing 150 ml of 80% acetic acid and 15 ml of conc. Nitric acid. Prepare fresh Anthrone reagent by dissolving 200 mg anthrone in 100 ml concentrated sulphuric acid and chill for 2 hours before use. Prepare 67% sulphuric acid by mixing 68 ml Conc. Sulphuric acid and 32 ml distilled water.

After preparing the above solutions add 3 ml acetic/nitric reagent to a known amount (100 mg) of the sample in a test tube and mix in a vortex mixer for 5 minutes. Place the tube in a waterbath at 100^{o}C for 30 minutes and then centrifuge the contents for 15-20 minutes. Discard the supernatant. Wash the residue with distilled water. Then add 10 ml of 67% Sulphuric acid and allow it to stand for 1 hour. Dilute 1 ml of the above solution to 100 ml. To 1 ml of this diluted solution, add 10 ml of anthrone reagent and mix well. Heat the tubes in a boiling water bath for 10 minutes. Cool and measure the colour at 630 nm in spectrophotometer by setting a blank with anthrone reagent and distilled water.

Take 100 mg cellulose in a test tube and proceed the steps of creating the standard by addition of sulphuric acid to anthrone reagent as above procedure.

$$= \frac{OD_{sample}}{OD_{standard}} \times \text{conc. of standard} \times \frac{Volume_{total}}{Volume_{taken}} \times \frac{Volume_{made\ up}}{\text{Weight of sample}} \times 100$$

vi) Determination of Hemicellulose

Holocellulose = Cellulose + Hemicellulose (Rowell, 2013)

vii) Ash content (ASTM D1102-84, 1984)

Two grams of oven dry powdered wood meal was placed in an empty crucible and kept inside muzzle furnace at 575±25^{o}C for 3 hours.

3.3.4 MECHANICAL PROPERTIES

Assessment of mechanical properties was carried out in the Central Wood Testing Laboratory under the Rubber Board of India, Kottayam, Kerala.

3.3.4.1 Testing Instrument

All the mechanical properties except tensile strength parallel to grain were tested using an automatic Universal Testing Machine (UTM-Shimadzu 100 KgN) which is a computerized and sophisticated version of the manual UTM (Plate 10a). The testing units consist of a jig where the samples are loaded for test and a head, whose upward or downward movement applies stress to the sample. The calibration of the instrument is controlled by a control keypad. This set up is associated with a computer installed with the software “Winsoft", which sense the deflection and stress, and plots the load by deflection curve on the monitor simultaneously with the test. Before the start of a test, the instrument is calibrated for the type of test rate of loading and dimensions of the samples as per IS 1708: 1986 (ISI, 1986).

On completion of the test, the stress by strain graph can be directly read from the monitor and various parameters corresponding to the test can be recorded.

3.3.4.2 Preparations of test samples

Scantlings were air dried. Then the scantlings were converted to standard small clear specimens for different tests as per IS 1708: 1986 specified by ISI (1986). The samples were transferred to a conditioning chamber to condition all the samples to a uniform moisture content of 12±2 percent.

3.3.4.3 Testing of samples

The following tests for wood mechanical properties were conducted as per IS 1708: 1986.

i) Static bending test

Samples of size 2 cm x 2 cm cross section and 30 cm length were tested as per IS 1708 (part 5): 1986 (ISI, 1986). Before loading the sample for testing, the width and thickness were accurately measured. The samples were loaded such that the stress was perpendicular to the grain (Plate 10e). The machine was calibrated to set the deflection and load at zero and the rate of loading was set at I mm per minute. Load by deflection curve was read from the monitor. The parameters viz., Modulus of Elasticity (MOE), Modulus of Rupture (MOR), maximum load, Fibre Stress at the Limit of Proportionality (FS at LP) and Horizontal Shear at the Limit of Proportionality (HS at ML) were estimated from further analysis. The software calculates MOE over a range of deflection at the limit of proportionality. To overcome this discrepancy, the tangent of the curve was adjusted to the maximum and deflection corresponding to the proportionality limit was recorded. By substituting the value thus attained in the following formulae, various parameters were estimated.

(a) Fiber Stress at Limit of Proportionality (FS at LP) (kg cm^{-2}) = $\frac{3PL}{2BH^2}$

(b) Modulus of Rupture (MOR) (kg cm^{-2}) = $\frac{3PL}{2BH^2}$

(c) Modulus of Elasticity (MOE) (kg cm^{-2}) = $\frac{PL^3}{4\Delta BH^3}$

(d) Horizontal Shear at Limit of Proportionality (HS at LP) (kg cm^{-2}) = $\frac{3P}{4BH}$

(e) Horizontal Shear stress at Maximum Load (HS at ML) (kg cm^{-2}) = $\frac{3P'}{4BH}$

Where,

P = Load in kg at the limit of proportionality which shall be taken as the point in load deflection curve above which the graph deviates from the straight line

I = Span of the test specimen in cm

B = Breadth of test specimen in cm

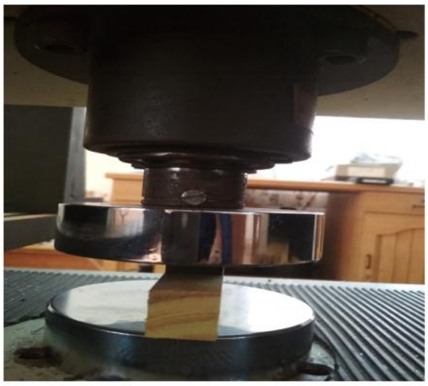
H = Depth of the test specimen in cm

P' = Maximum load in kg

A = Deflection in cm at the limit of proportionality

a

b



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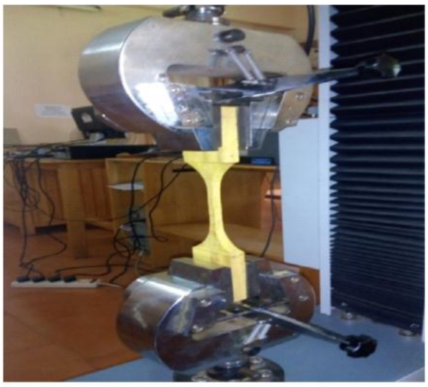

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Plate 10: (a) UTM at CWTL, Kottayam, Kerala, (b) Compression strength Parallel to grain, (c) Compression strength Perpendicular to grain, (d) Tensile strength, (e) Static bending

ii) Test for compression strength parallel to grain

Samples of size 2 cm x 2 cm x 8 cm were tested as per IS 1708 (part 8): 1986 (ISI, 1986). Before the test, the width, thickness and length of the samples were recorded. The rate of loading was calibrated to 0.6 mm per minute and the load and deflection was set to zero. The sample was loaded with its longitudinal axis along the direction of movement of the head (Plate 10b). Load- deflection curve is analyzed through the reanalysis mode. A tangent is drawn in such a way that maximum number of points are in the straight line. Based on the limit of proportionality and maximum load, the compressive stress at limit proportionality, compressive stress at maximum load and Modulus of Elasticity were calculated using the formula

(a) Compressive Stress at Limit of Proportionality (CS at LP) (kg cm^{-2}) = $\frac{P}{A}$

(b) Compressive Stress at Maximum Load (CS at ML) (kg cm^{-2}) = $\frac{P'}{A}$

(c) Modulus of Elasticity in Compression parallel to grain (kg cm^{-2}) = $\frac{PL}{\Delta A}$

Where,

P = Load at limit of proportionality in kg
A = Cross sectional area of specimen in cm^2
P' = Maximum crushing load in kg
L= Length of the specimen in cm
Δ = Deformation at the limit of proportionately in cm

iii) Test for compression strength perpendicular to grain

Samples of size 2 cm x 2 cm cross section and 10 cm length were tested as per IS 1708 (Part 9): 1986 (ISI, 1986). The sample was loaded such that the vertical plane faces the stress (Plate 10c). The linear dimensions of the sample were recorded before the test. The rate of loading was calibrated to 0.6 mm per minute and the deflection and load were set to zero. Various parameters were read from the monitor and graph adjusted to reanalyze the MOE. The following parameters were calculated using the formula,

(a) Compressive Stress at Limit of Proportionality (kg cm^{-2}) = $\frac{P}{A}$

(b) Crushing Strength at compression of 2.5 mm (kg cm^{-2}) = $\frac{P'}{A}$

(c) Modulus of Elasticity in Compression perpendicular to grain (kg cm^{-2}) = $\frac{PH}{\Delta A}$

Where,

P = Load at the limit of proportionately in kg

A = Area of cross-section normal to the direction of load or area of a metal plate used 3 cm x 2 cm.

P'= Load at 2.5 mm compression in kg

H = Height of the specimen in cm

Δ = Deformation at the limit of proportionality in cm

iv) Tensile strength parallel to grain

The test has been carried out using Universal Testing Machine (Kalpak, K-test series, 15 KN). Samples of 5 cm and 1.5 cm cross section and 32.5 cm in length were tested as per IS 1708 (part 12): 1986 (1SI, 1986). The machine was calibrated to set the deflection and load at zero and the rate of loading was set at 1 mm per minute (Plate 10d). Based on the limit of proportionality and maximum load, tensile strength at limit of proportionality and tensile strength at maximum load were calculated using the formula,

(a) Tensile Stress at Limit of Proportionality (TS at LP) (kg cm^{-2}) = $\frac{P}{A}$

(b) Tensile Stress at Maximum Load (TS at ML) (kg cm^{-2}) = $\frac{P'}{A}$

Where,

P = Load at limit of proportionality

P'= Maximum load in kg

A = Cross sectional area of specimen in cm^2

3.3.5 Statistical analysis

The present study was to observe the variation in wood properties of Jack trees collected from three different altitudinal zones of Thrissur district, Kerala (ENVIS, 2017). The sampling and sub sampling gives rise to nested or hierarchial classification. Therefore, to analyze the data on different wood properties and their interrelationships with one another, the model for analysis followed was NESTED ANOVA which was carried out using SPSS (Ver. 21).

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4. RESULTS

The results obtained from the present investigation entitled **"Wood property variation in jack trees (*Artocarpus heterophyllus* Lam.) grown in Thrissur district, Kerala"** carried out in the Laboratory and Wood Workshop at the Department of Forest Products and Utilization, College of Forestry, Kerala Agricultural University, Thrissur, Kerala during 2017-2020 are presented in this chapter. The data obtained from the study were subjected to appropriate statistical analysis and the results obtained are presented below under the following headings:

4.1) Physical properties of wood
4.2) Chemical properties of wood
4.3) Anatomical properties of wood
4.4) Mechanical properties of wood
4.5) Simple correlation coefficients
4.6) Regression Studies

4.1) PHYSICAL PROPERTIES OF WOOD

4.1.1) Colour and Texture

Wood is a natural and one of the most valuable raw materials with variations in properties of texture, colour, density and strength have been used for many purposes (Ates *et al.*, 2009). Colour is a crucial factor in hardwood appearance. It is often considered important in assessing aesthetic value of the wood product. The colour variation within a species is influenced by many natural factors *viz*., soil types, minerals, water levels, available sunlight, temperature and genetic composition.

Colour of the wood samples of Jack tree collected from different sites were quantitatively measured in reflectance mode as CIELAB colour co-ordinates (10° standard observer, D65 standard illuminant) using Hunter Lab Scan XE colorimeter at Institute of Wood Science and Technology (IWST), Bangalore, Karnataka.

Table 2. Variation in Colour parameter (L*) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	59.78 (2.91)	58.31 (2.97)	59.27 (1.46)
60cm-90cm	59.96 (4.18)	58.61 (6.41)	61.44 (2.46)
90cm-120cm	61.32 (1.26)	56.69 (6.81)	57.98 (4.52)
Zone mean	60.35	57.87	59.56
F value	2.98 ^{ns} (Zones)		0.29 ^{ns} (Girth classes within zones)

- **Value in parenthesis is standard deviation; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 3. Variation in Colour parameter (a*) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	9.83 (0.43)	10.49 (1.19)	10.85 (0.29)
60cm-90cm	10.68 (0.42)	11.19 (1.64)	9.69 (0.66)
90cm-120cm	10.08 (0.18)	11.75 (1.39)	11.81 (1.49)
Zone mean	10.20	11.14	10.78
F value	1.21^{ns} (Zones)		1.66 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The Table 2 shows the values for L* value (lightness index), the highest value was found for wood of 60 cm -90 cm girth class which belongs to highland *i.e.* 61.44 and lowest value for 90 cm -120 cm girth class *i.e.* 56.69 from midland. The highest zonal mean value of 60.35 was found for lowland and the lowest zonal mean value for midland *i.e.* 57.87. The analysis on the current data showed no significant variation between the zones and also girth within the zones. As the values recorded are closer towards 100 for L* component, it shows the colour of the wood tend more towards whiteness than darkness.

Table 3 shows the data for values for a* value (redness index) for which the wood belongs to 90 cm -120 cm girth class has the highest value 11.81 and the lowest value 9.69 for 60 cm -90 cm girth class. When taking the zone mean, the highest value is for wood belongs to midland *i.e.* 11.14 and the lowest value of 10.20 for lowland. There was no significant variation observed between the zones and girth within zones. As the values recorded are positive for a* component, it shows the colour of the wood has more redness than greenness.

Table 4. Variation in Colour parameter (b*) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	40.08 (1.62)	38.90 (3.96)	38.71 (2.53)
60cm-90cm	38.23 (4.15)	38.80 (3.29)	40.42 (2.78)
90cm-120cm	41.62 (2.44)	40.02 (2.23)	37.07 (5.32)
Zone mean	39.97	39.25	38.73
F value	0.57 ^{ns} (Zones)		0.56 ^{ns} (Girth classes within zones)

- **Value in parenthesis is standard deviation; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The b* value (yellowness index) from the Table 4 shows the highest value 41.62 for the wood which belongs to 90 cm -120 cm girth class from lowland and the lowest for 90 cm -120 cm girth class *i.e.* 37.07 which belongs to highland. When it comes to the zone mean value, the highest value 39.97 was found for the wood which belonged to lowland and the lowest zonal mean value for highland wood *i.e.* 38.73. There was no significant variation observed between the zones and girth within zones. As the values recorded are positive for b* component, it shows the colour of the wood has more yellowness than blueness. In the present study, heartwood colour showed no significant variation across the zones of Thrissur district, Kerala.

Table 5 shows the texture that has been observed from every wood which was procured from different zones. All the wood samples from the different girth classes within different zones had the medium texture wood.

Table 5. Variation in texture of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	Medium	Medium	Medium
60cm-90cm	Medium	Medium	Medium
90cm-120cm	Medium	Medium	Medium

4.1.2) Moisture content (%)

Wood is hygroscopic in nature and extent of its hygroscopicity depends upon the cellular components of wood. The water in wood is held in cellular cavities and cell wall. The water in cell wall is of more concern as it influences various wood properties including shrinkage and swelling. The moisture content and maximum moisture content in living trees vary by species and also due to sapwood and heartwood contents. The presence of moisture in wood makes it dimensionally unstable and it also indicate the degree of porosity in wood. The data related to moisture content of Jack wood collected from different sites are presented in Table 6. The maximum moisture content of 44.55% was observed for wooden samples collected from lowland which belongs to 60 cm -90 cm girth class and the minimum moisture content 35.65% was found in sample procured from midland which belongs to 30 cm -60 cm (Figure 4). The highest zonal mean value of 41.79% was observed for wood procured from lowland and the lowest zonal mean value for highland *i.e.* 38.89%. There was no significant variation observed between the zones and girth within zones.

Table 6. Variation in moisture content (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	40.15 (4.30)	35.65 (4.84)	37.22 (5.99)
60cm-90cm	44.55 (11.85)	41.63 (16.45)	41.71 (10.36)
90cm-120cm	40.68 (4.41)	40.20 (18.41)	37.75 (10.15)
Zone mean	41.79	39.16	38.89
F value	1.72^{ns} (Zones)		0.15^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.1.3) Specific gravity

Specific gravity is the most widely used criterion for depicting the strength of wood and is said to be affected by moisture, structure, extractives, and chemical composition (Tsoumis, 1991). It is a measure of the amount of structural material a tree species allocates to provide support and strength. It is a most principal wood characteristic because its knowledge allows the prediction of greater number of properties than any other trait (Zobel and Talbert, 1984; Bowyer and Smith, 1998) and is considered as one of the most informative property about the physico-mechanical behavior of wood used for timber, pulp and paper production (Lima *et al.*, 2000; Raymond and Muneri, 2001). Some wood properties that are closely related to wood's specific gravity are strength, dimensional stability, ability to retain paint, fiber yield per unit volume, suitability for making particleboard and related wood composite materials and suitability as a raw material for making paper (Bowyer and Smith, 1998).

Table 7. Variation in green specific gravity of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	0.51 (0.04)	0.60 (0.08)	0.53 (0.06)
60cm-90cm	0.47 (0.06)	0.56 (0.06)	0.53 (0.04)
90cm-120cm	0.57 (0.06)	0.58 (0.04)	0.54 (0.07)
Zone mean	0.52	0.58	0.53
F value	3.33^{ns} (Zones)		0.83^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Specific gravity and density are the important characteristics for wood quality evaluation. It has a tremendous effect on different wood physiological, ecological as well as morphological characteristics of the wood (Jerome *et al*., 2006). It can be taken as a crucial property and has a great effect on both solid and fibrous wood products (Bhat, 1985). Wanneng *et al.* (2014) also observed similar results in 10, 15, 20 and, 25 years old teak of different diameter classes. However, Bhat (1998) showed that mean specific gravity varied significantly between juvenile wood and mature wood of 65 years old teak trees grown in three locations in Kerala which is contrary to our findings.

Table 8. Variation in oven dry specific gravity of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	0.54 (0.03)	0.57 (0.01)	0.57 (0.02)
60cm-90cm	0.57 (0.01)	0.55 (0.01)	0.54 (0.03)
90cm-120cm	0.57 (0.02)	0.58 (0.03)	0.55 (0.03)
Zone mean	0.56	0.57	0.56
F value	0.00^{ns} (Zones)		1.94^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The different results obtained in the present study attributed to indistinct climatic variation and age effect of the sampled trees across three zones of Thrissur district, Kerala. As density is one of the most heritable characters. As density is one of the most heritable characters in wood, genotypic effect may be one of the reasons. From the Table 7, the highest green specific gravity 0.60 was found for the midland which belongs to 30 cm -60 cm girth class and the lowest value for 60 cm -90 cm girth class which belongs to lowland *i.e.* 0.47 (Figure 5). The highest zonal mean value for green specific gravity was observed for 0.58 and lowest zonal mean value for lowland *i.e.* 0.52. Analysis of data revealed that there was no significant variation present across three zones as well as between girth classes within zones of Thrissur district of Kerala.

Table 8 shows the data for oven dry specific gravity, the maximum value of 0.58 was observed for 90 cm -120 cm girth class which belongs to midland. The minimum value for 30 cm -60 cm girth class wood which belongs to lowland and 60 cm -90 cm girth class of highland *i.e.* 0.54 (Figure 6). The zone mean value shows the maximum for midland *i.e.* 0.57 and the minimum for both lowland and highland. The data shows no significant variation across three zones as well as between girth classes within zones of Thrissur district of Kerala.

4.1.4) Shrinkage (%)

The wood cell wall is mainly composed of polymers with hydroxyl and other oxygen-containing groups that attract moisture through hydrogen bonding. Swelling increases until the cell wall is saturated with water. This point is called the fiber saturation point, and ranges from 20 to 50 per cent in weight gain (Feist and Tarkow, 1967). Water, beyond this point is free water in the void structure and does not contribute to further swelling. This process is reversible, and wood shrinks as it loses moisture below the fiber saturation point. Sorption is combined term for swelling and shrinkage. Many thermodynamic models have been used to describe moisture sorption in wood below fiber saturation point. Although these models differ in their parameters and physical interpretation, they all divide water into two types, tightly bound water and less tightly bound water (Simpson, 1980).

Table 9. Variation in volumetric shrinkage (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	3.93 (1.97)	4.78 (2.17)	3.91 (1.98)
60cm-90cm	3.63 (1.90)	5.38 (2.32)	3.82 (1.94)
90cm-120cm	4.26 (2.06)	4.79 (2.18)	3.47 (1.84)
Zone mean	3.94 ^{a}	4.98 ^{b}	3.73 ^{a}
F value	13.22* (Zones)		0.29 ^{ns} (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

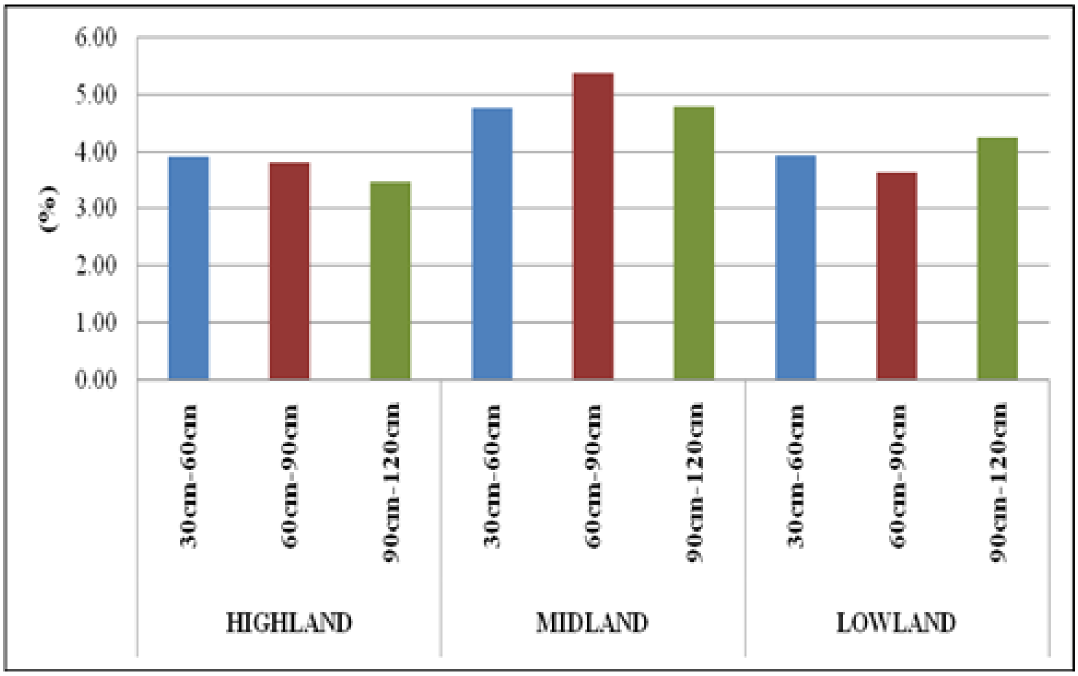

Fig. 1. Volumetric Shrinkage (%) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

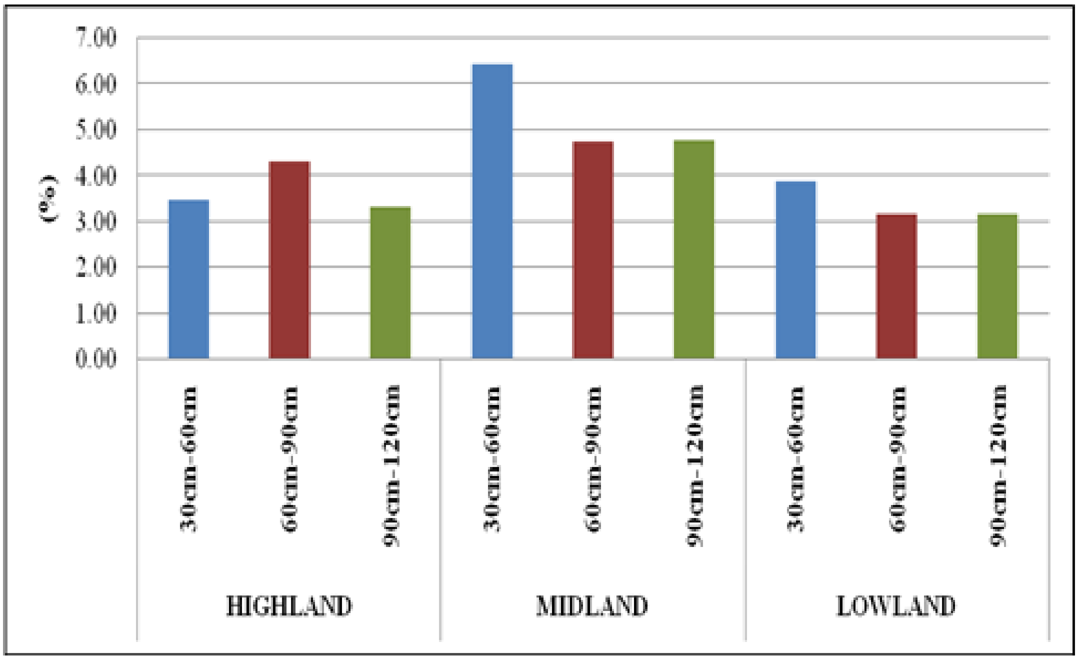

Fig. 2. Tangential Shrinkage (%) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

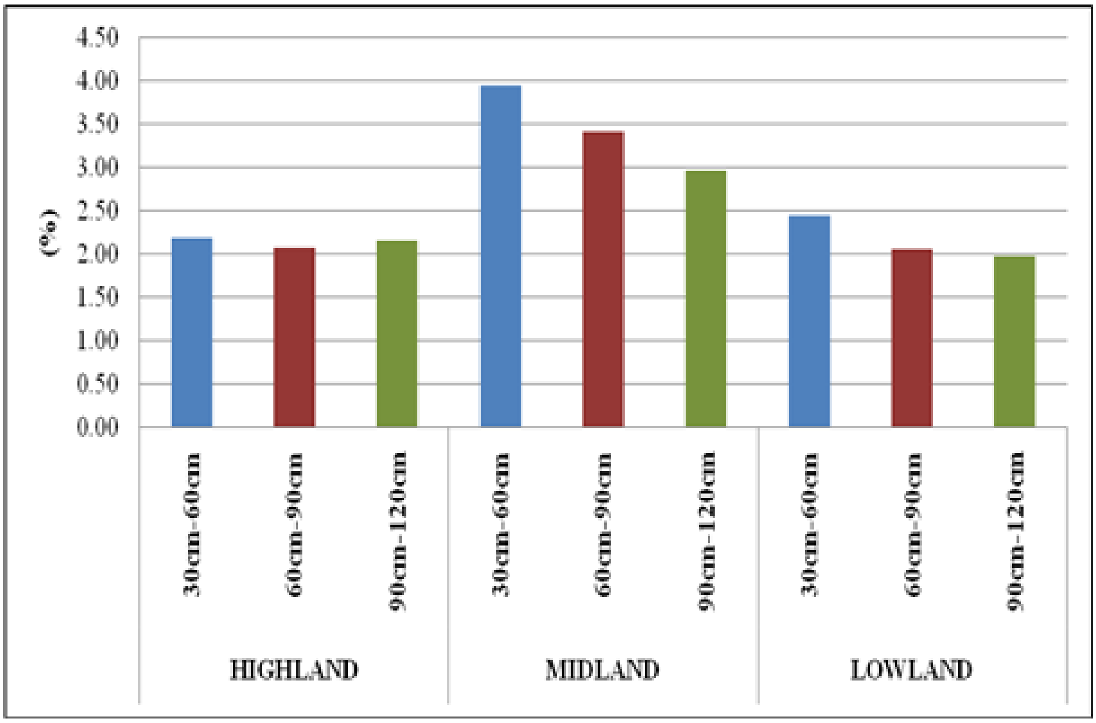

Fig. 3. Radial Shrinkage (%) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

Table 10. Variation in tangential shrinkage (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	3.90 (1.97)	6.45 (2.53)	3.48 (1.84)
60cm-90cm	3.18 (1.77)	4.73 (2.14)	4.31 (2.02)
90cm-120cm	3.16 (1.76)	4.77 (2.16)	3.31 (1.80)
Zone mean	3.41 [a]	5.32 [b]	3.70 [a]
F value	7.00* (Zones)		0.58 [ns] (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 11. Variation in radial shrinkage (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	2.45 (1.56)	3.95 (1.98)	2.18 (1.46)
60cm-90cm	2.06 (1.43)	3.42 (1.81)	2.07 (1.43)
90cm-120cm	1.98 (1.39)	2.96 (1.71)	2.15 (1.45)
Zone mean	2.17 [a]	3.44 [b]	2.13 [a]
F value	16.19* (Zones)		0.38 [ns] (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Tangential shrinkage is always higher and average of radial shrinkage values range from about 2 to 8 per cent (Hoadley, 1998). Wood high in water soluble extractives were found to be shrink less due to the bulking effect of extractive which left in the cell walls. (Stamm *et al.,* 1946). The data in the Table 9 shows the observations for volumetric shrinkage of the respective girth classes within the three zones. The highest value was observed for the wood which belongs to 60 cm -90 cm girth class of midland *i.e.* 5.38% and the lowest value 3.47% was observed for 90 cm -120 cm girth class of highland (Fig. 1). The maximum value of zonal mean of 4.98% was observed for midland and the lowest zonal mean value for highland *i.e.* 3.73%. Analysis of the data revealed significant variation between zones and not between girth classes within zone.

Table 10 shows the observations for tangential shrinkage for the three zones in which the maximum value of 6.45% was recorded for the wood samples of 30 cm -60 cm girth class from midland and the minimum value for 90 cm -120 cm *i.e.* 3.16% from lowland (Fig. 2). The highest zonal mean value was observed for midland *i.e.* 5.32% and the lowest zonal mean value 3.41% for lowland. The highest radial shrinkage was observed for the wood samples procured from midland (Fig. 3) *i.e.* 3.95% which belongs to 30 cm -60 cm girth class and the lowest value for the wood collected from lowland which belongs to 90 cm -120 cm girth class *i.e.* 1.98% (Table 11). The highest zonal mean value of 3.44% was recorded for midland and the lowest zonal mean value for highland *i.e.* 2.13%. For both tangential and radial shrinkage, significant variation was observed for the zones and no variation for girth classes within the zones.

4.2) CHEMICAL PROPERTIES OF WOOD

4.2.1) Water soluble extractives

4.2.1.1) Cold water-soluble extractives (%) and Hot water-soluble extractives (%)

The cold-water soluble compounds in wood are generally sugars, salts, tannins and gums. The species which contain large number of extractives have better durability, dimensional stability and plasticization. Extractive contents consist of lipids (terpenoide, fat, wax, fatacids) and phenolics (single phenolics, stilbenel, lignane, flavonoide, tannin). The most amounts of ingredients can be found in core wood, wood rays, root wood, branch formation and at the bark. The above-mentioned ingredients define wood colour, smell and durability as well as quality of pulping and drying and also the gluing properties (Lange and Schwager, 1997).

The maximum value of cold-water solubility was recorded for wood samples procured from highland *i.e.* 4.55% which belongs to 60 cm -90 cm girth class and the minimum value of 1.81% for 30 cm -60 cm girth class which belongs to lowland. The highest zonal mean value was noticed for highland *i.e.* 3.40% and the lowest zonal mean value 1.97% for lowland (Table 12). A critical observation of the data revealed no significant variations among zones and girth classes within the zones.

Table 12. Variation in cold water-soluble extractives (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	1.81 (1.32)	2.19 (1.44)	2.31 (1.51)
60cm-90cm	2.19 (1.47)	2.39 (1.50)	4.55 (2.09)
90cm-120cm	1.91 (1.38)	2.50 (1.56)	3.32 (1.81)
Zone mean	1.97	2.36	3.40
F value	4.44^{ns} (Zones)		0.82^{ns} (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The highest value for hot water solubility was observed for 60 cm -90 cm girth class wood which belongs to highland *i.e.* 7.28% and the lowest value of 3.75% for 30 cm -60 cm girth class which procured from lowland (Table 13). The maximum zonal mean value was recorded for highland (7.11%) and the lowest zonal mean value for lowland *i.e.* 5.27%. There was no significant variation observed between the zones and girth within zones.

Table 13. Variation in hot water-soluble extractives (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	3.75 (1.92)	6.05 (2.46)	6.94 (2.63)
60cm-90cm	6.47 (2.53)	6.77 (2.59)	7.28 (2.69)
90cm-120cm	5.59 (2.36)	6.16 (2.47)	7.11 (2.65)
Zone mean	5.27	6.33	7.11
F value	3.22^{ns} (Zones)		1.56^{ns} (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.2.2) Chemical soluble extractives

4.2.2.1) Alcohol benzene soluble extractives

Alcohol-benzene solubility of wood is an important character representing extractives present in wood which affect the quality of pulp. The components which are generally soluble in alcohol-benzene are oleoresins, fats and waxes. Table 14 shows the data for alcohol benzene soluble extractives content inside Jack wood. The maximum value of 15.91% was recorded for 60 cm -90 cm girth class which belongs to lowland and the lowest for highland 10.49% which belongs to 30 cm -60 cm (Fig. 4). The highest zonal mean value of 13.91% was observed for lowland and the lowest zonal mean value for the zones for midland *i.e.* 12.19%. There was no significant variation between zones but significant variation was found for the girth classes within zones.

Table 14. Variation in alcohol-benzene extractives (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	10.69 ^{A} (3.27)	12.44 ^{A} (3.53)	10.49 ^{A} (3.22)
60cm-90cm	15.91 ^{B} (3.99)	12.54 ^{A} (3.54)	13.47 ^{A} (3.67)
90cm-120cm	15.13 ^{B} (3.88)	11.58 ^{A} (3.40)	12.84 ^{A} (3.58)
Zone mean	13.91 ^{a}	12.19 ^{a}	12.27 ^{a}
F value	0.70 ^{ns} (Zones)		5.08* (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.2.2.2) Klason lignin content

Lignin is the adhesive or binder in wood that holds the fibers together (Biermann, 1996). In case of pulp and paper making or bioethanol production, isolation of lignin become an important factor. Lignin can reduce paper strength because it could be a barrier for hydrogen bonding in the fiber formation. Lignin can reduce paper strength because it could be a barrier for hydrogen bonding in the fiber formation.

Table 15. Variation in klason lignin content (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	27.67 (5.26)	30.77 (5.53)	25.23 (5.02)
60cm-90cm	30.65 (5.53)	24.27 (4.91)	29.11 (5.38)
90cm-120cm	26.32 (5.12)	29.41 (5.42)	23.47 (4.84)
Zone mean	28.21	28.15	25.93
F value	0.61^{ns} (Zones)		1.93^{ns} (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The possible reason for variation in cell wall constituents can be assigned to the varied production of dry matter. In the case of Jack wood, the value for klason lignin which was recorded for the wood obtained from the three different zones belonging to the three different girth classes given in Table 15 showed highest value for midland with 30.77% which belongs to 30 cm -60 cm girth class and the lowest for highland of 90 cm -120 cm girth class *i.e*. 23.47%. The highest zonal mean value of 28.21% was observed for lowland and lowest zonal mean value for highland *i.e.* 25.93%. There was no significant variation observed between the zones and girth within zones.

4.2.2.3) Holocellulose content

Holocellulose, which constitute cellulose and hemicelluloses is the major portion of fibrous raw material. Cellulose and hemicellulose together described as holocellulose is used to denote the polysaccharides in wood. The holocellulose content is a quantitative indication of fibrous raw material influencing consideration of its suitability for pulp.

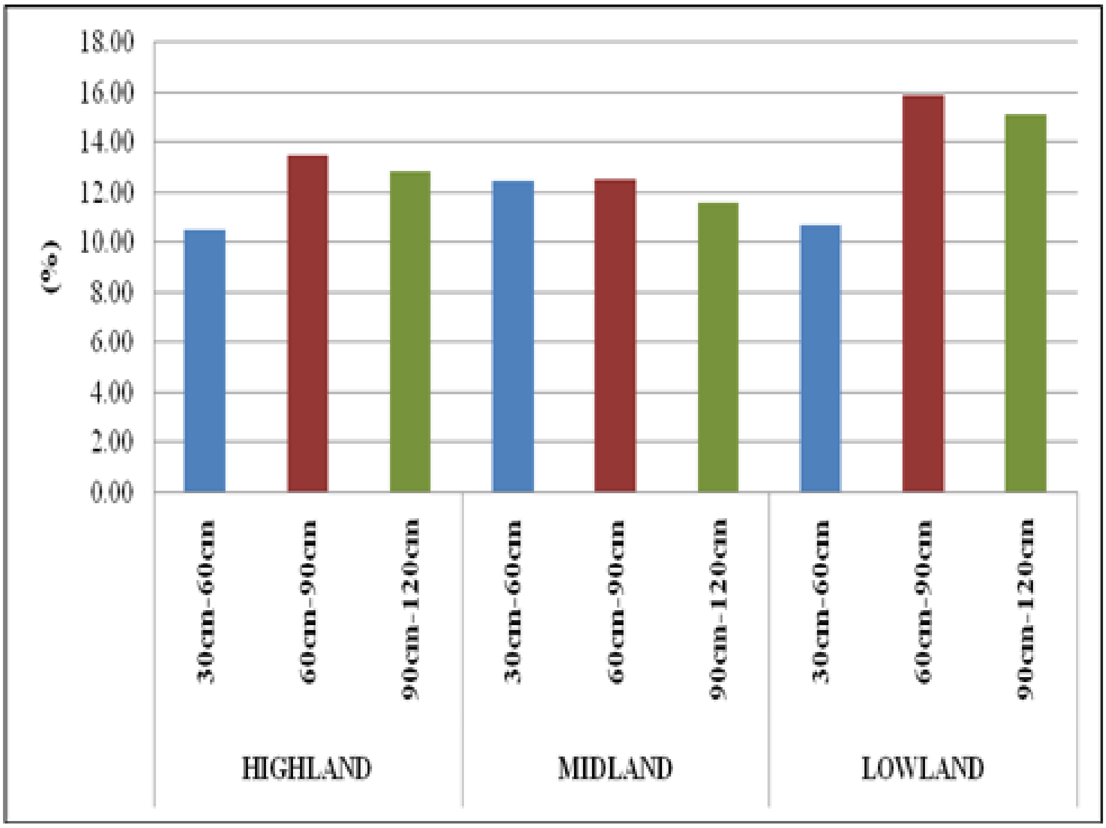

Fig. 4. Alcohol Benzene Soluble Extractives (%) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

Table 16. Variation in holocellulose content (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	66.19 (8.13)	72.67 (8.52)	69.41 (8.33)
60cm-90cm	70.55 (8.40)	76.13 (8.72)	69.47 (8.33)
90cm-120cm	70.06 (8.37)	65.46 (8.09)	70.24 (8.38)
Zone mean	68.93	71.42	69.71
F value	0.38^{ns} (Zones)		2.53^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Whereas, lignin is a phenolic substance consisting of an irregular array of variously bonded hydroxyl and methoxy-substituted phenyl-propane units, which is distributed throughout the secondary cell wall with the highest concentration in middle lamella and is responsible for providing stiffness to the cell wall (Rowell, 2005). It also serves to bond individual cells together in the middle lamella region. The data in Table 16 shows the percentage of holocellulose content in the wood obtained from different zones which belongs to the respective girth classes which showed no significant variation. The highest value for holocellulose obtained *i.e.* 76.13% from midland which belongs to girth class of 60 cm -90 cm and lowest value of 65.46% for midland which belongs to girth class of 90 cm -120 cm. The highest zonal mean value of 71.42% was recorded for midland the lowest zonal mean value for lowland *i.e.* 68.93%. There was no significant variation observed between the zones and between girth within zones.

4.2.2.4) Cellulose and Hemicellulose content

From the Table 17, the highest value for cellulose *i.e.* 46.02% which is obtained from highland which belongs to 60 cm -90 cm girth class whereas the lowest 38.95% from lowland which was of 30 cm -60cm girth class. The maximum zonal mean value of 44.33% was recorded for midland and the lowest zonal mean value for lowland *i.e.* 41.61%. In case of the percentage of cellulose content which is analysed from different showed no significant variation between the zones and girth classes within zones. For hemicellulose as from the Table 18, the highest value of 32.95% which was obtained from midland which belongs to 60 cm -90 cm. The lowest value of 23.45% which is obtained from 60 cm -90cm girth class of highand. The highest zonal mean value of 29.12% was observed for the wood procured from midland and the lowest zonal mean value was recorded for highland *i.e.* 25.38%. As cellulose, the hemicellulose content showed no variation difference between zones.

Table 17. Variation in cellulose content (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	38.95 (6.23)	44.46 (6.68)	44.20 (6.39)
60cm-90cm	42.65 (6.20)	43.19 (6.54)	46.02 (6.53)
90cm-120cm	43.24 (6.56)	39.24 (6.25)	42.76 (6.07)
Zone mean	41.61	42.30	44.33
F value	0.54 ^{ns} (Zones)		0.61 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

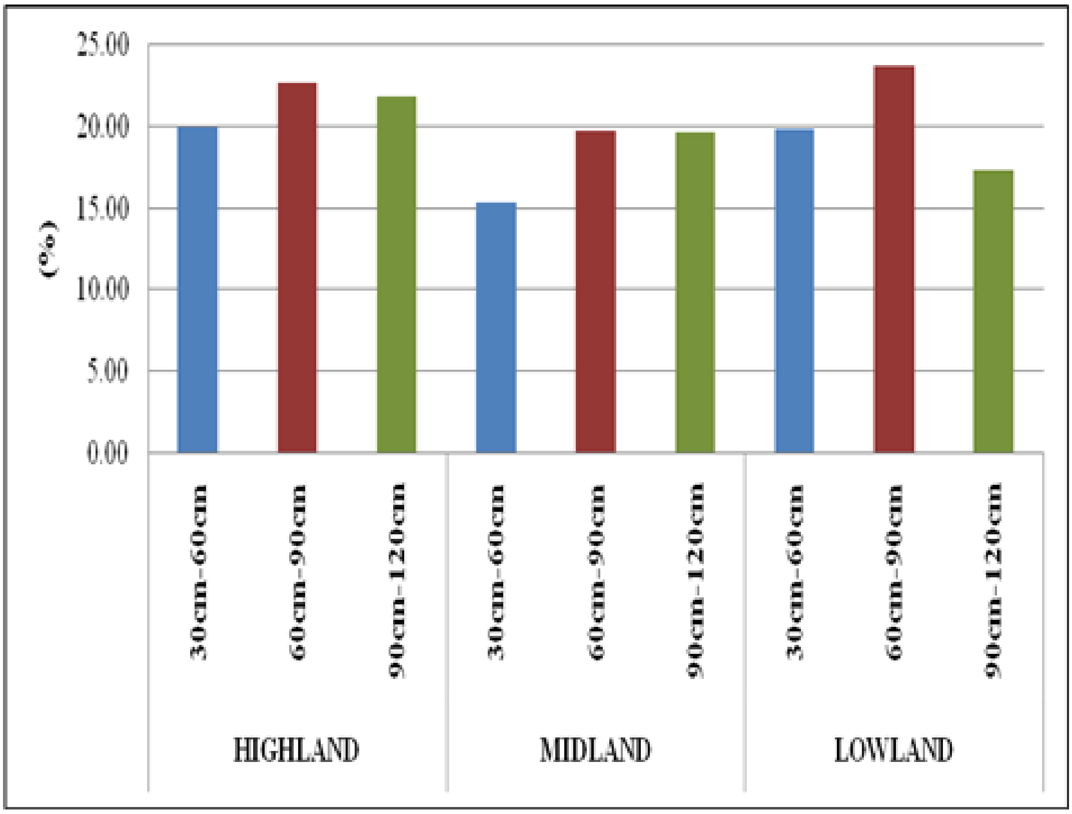

Fig.5. NaOH soluble extractives (%) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

Table 18. Variation in hemicellulose content (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	27.24 (5.22)	28.21 (5.26)	25.21 (5.29)
60cm-90cm	27.90 (5.62)	32.95 (5.75)	23.45 (5.14)
90cm-120cm	26.82 (5.08)	26.22 (5.11)	27.49 (5.76)
Zone mean	27.32	29.12	25.38
F value	0.07 ^{ns} (Zones)		0.61 ^{ns} (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.2.2.5) NaOH solubility and Ash content

Table 19 and Table 20 shows the value of sodium hydroxide soluble extractives and ash content of the Jack wood obtained from the different girth classes respectively. The results show that the highest value of 22.70% for NaOH solubility is from highland wood which belongs to 60 cm -90 cm girth class whereas the lowest value for midland *i.e.* 15.32% which belongs to 30 cm-60 cm girth class (Fig. 5). The highest zonal mean value was observed for highland *i.e.* 21.48% and the lowest zonal mean value (18.26%) for midland.

Table 19. Variation in NaOH solubility (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	19.83 (5.46)	15.32 (5.31)	19.92 (4.45)
60cm-90cm	23.76 (4.85)	19.79 (5.454)	22.70 (4.76)
90cm-120cm	17.34 (5.23)	19.67 (5.93)	21.82 (4.99)
Zone mean	20.31 ^{b}	18.26 ^{b}	21.48 ^{a}
F value	5.69* (Zones)		1.68 ^{ns} (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 20. Variation in ash content (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	0.52 (0.71)	0.66 (0.81)	0.58 (0.76)
60cm-90cm	0.76 (0.85)	0.80 (0.88)	0.50 (0.70)
90cm-120cm	0.74 (0.86)	0.94 (0.97)	0.89 (0.94)
Zone mean	0.67	0.80	0.66
F value	0.68 ^{ns} (Zones)		1.66 ^{ns} (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

There was significant variation observed between the zones but not for girth within zones. The highest value of 0.94% for ash content was from midland of 90 cm -120 cm girth class whereas the lowest value of 0.5% was from highland which belongs to 60 cm -90 cm girth class (Table 19). The maximum zonal mean value of 0.80% was observed for midland and the minimum zonal mean value of 0.67% was recorded for lowland. There was no significant variation observed between the zones and between girth classes within zones.

4.3) ANATOMICAL PROPERTIES OF WOOD

4.3.1) Fibre morphology

4.3.1.1) Fibre length and Fibre diameter

The size and compactness of fibres in wood gives the level of strength and resistance of wood. They are elongated type with much lignified cell wall. The maximum value for fibre length was recorded for 30 cm -60 cm girth class *i.e.* 1139.06µm which belongs to highland zone and the minimum value *i.e.* 1040.43µm for lowland which belongs to 30 cm -60 cm girth class (Table 21).

Table 21. Variation in fibre length (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	1040.43 (76.44)	1047.27 (67.33)	1139.06 (21.38)
60cm-90cm	1083.13 (9.94)	1089.40 (112.49)	1063.84 (63.32)
90cm-120cm	1040.44 (60.83)	1072.57 (60.04)	1077.17 (12.24)
Zone mean	1054.67	1069.75	1093.36
F value	1.28^{ns} (Zones)		0.68^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The highest zonal mean value for fibre length was observed for highland *i.e.* 1093.36 µm and the lowest zonal mean value of 1054.67 µm for lowland. There was no significant variation observed between the zones and between girth classes within zones. In Table 22, the data shows the value for fibre diameter in which the highest value was observed for wood procured from lowland *i.e.* 22.23 µm which belongs to 60 cm -90 cm girth class. The lowest value of 20.10 µm was recorded for highland which belongs to girth class of 60 cm -90cm. The highest zonal mean value of 22.30 µm was noticed for lowland and lowest zonal mean value for midland *i.e.* 21.02 µm. There was no significant variation observed between the zones and between girth classes within zones.

Table 22. Variation in fibre diameter (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	21.45 (0.88)	20.45 (0.27)	22.11 (1.30)
60cm-90cm	23.22 (1.94)	20.91 (0.67)	20.10 (0.28)
90cm-120cm	22.23 (2.44)	21.69 (0.99)	22.15 (0.69)
Zone mean	22.30	21.02	21.45
F value	1.49^{ns} (Zones)		1.59^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.3.1.2) Lumen width and Wall thickness

The data in the table 23 gives the values of lumen width which was obtained by analyzing the fibre morphology which in turn contributes to the over strength and durability of wood.

Table 23. Variation in lumen width (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	13.76 (1.19)	11.58 (1.17)	14.67 (1.29)
60cm-90cm	15.66 (1.68)	12.19 (0.83)	12.55 (0.56)
90cm-120cm	14.13 (0.60)	15.17 (1.09)	13.29 (1.03)
Zone mean	14.52	12.98	13.50
F value	0.96^{ns} (Zones)		2.22^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 24. Variation in wall thickness (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	3.85^{B} (0.21)	4.43^{B} (0.45)	4.22^{A} (0.39)
60cm-90cm	3.78^{A} (0.34)	4.03^{AB} (0.49)	3.77^{A} (0.41)
90cm-120cm	3.88^{A} (0.47)	3.26^{A} (0.05)	4.43^{A} (0.17)
Zone mean	3.84^{a}	3.91^{a}	4.14^{a}
F value	1.34^{ns} (Zones)		3.19* (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

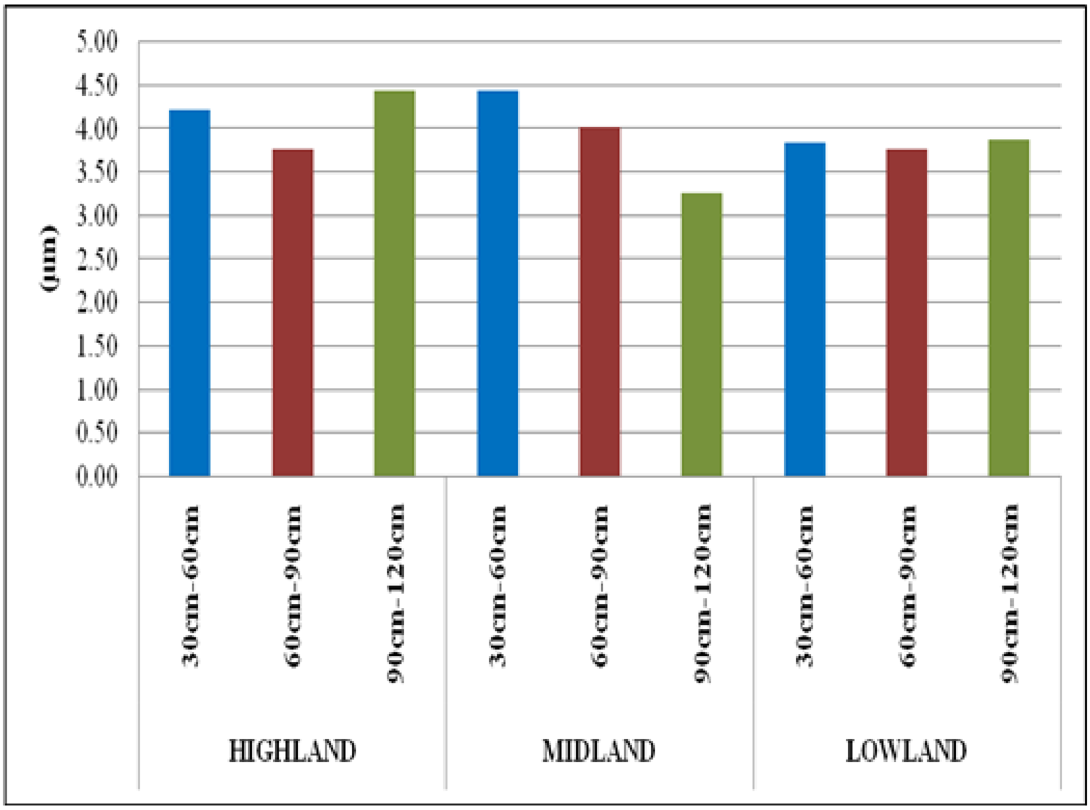

Fig. 6. Wall Thickness (µm) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

The maximum value for lumen width was recorded for lowland which belongs to 60 cm -90 cm *i.e.* 15.66 µm and the minimum value of 11.58 µm was observed for the wood procured from midland which belongs to 30 cm -60 cm girth class. The highest zonal mean lumen width was observed for lowland *i.e.* 14.52 µm and the lowest zonal mean value of 12.98 µm for midland. There was no significant variation observed between the zones and between girth classes within zones.

Table 24 shows the values of wall thickness recorded from analyzing the fibre morphology using the accurate tools with the help of fibre diameter and lumen width. The maximum wall thickness of 4.43 µm was observed for 30 cm -60cm girth class which belongs to midland and for 90 cm -120 cm which belongs to lowland (Fig. 6). The highest zonal mean value was observed for highland *i.e.* 4.14 µm and the lowest zonal mean value of 3.84 µm for lowland. There was no significant variation observed between the zones whereas variation was observed for girth classes within zones.

4.3.1.3) Runkel ratio and Slenderness ratio

Runkel ratio which refers to the ratio between double the wall thicknesses and lumen diameter is a commonly used indicator of the collapsibility of tracheids (Evans *et al.*, 1997). Singh *et al.* (1991) reported that fibre characteristics such as the Runkel ratio and shape factor had marked influence on strength properties. The tensile index, tear index and burst index decreased with increase in the Runkel ratio and shape factor. Runkel ratio of the fibres determines its felting power and flexibility.

The data in table 25 and table 26 shows the values for runkel ratio and slenderness ratio respectively which is being derived from the parameters obtained from the fibre morphology which in turn helps the wood to be used especially for the pulp and paper industry. The maximum value for runkel ratio was observed for wood collected from midland *i.e.* 0.78 which belongs to 30 cm -60 cm girth class. The minimum value of 0.43 was recorded for 90 cm -120 cm girth class procured from midland. The highest zonal mean value of 0.63 was noticed for midland and the lowest zonal mean value for lowland (0.53). There was no significant variation observed between the zones and for girth classes within zones.

Table 25. Variation in runkel ratio of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	0.56 (0.07)	0.78 (0.15)	0.58 (0.08)
60cm-90cm	0.49 (0.06)	0.68 (0.08)	0.60 (0.09)
90cm-120cm	0.55 (0.09)	0.43 (0.04)	0.67 (0.08)
Zone mean	0.53	0.63	0.62
F value	0.75^{ns} (Zones)		1.45^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 26. Variation in slenderness ratio of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	96.98 (3.50)	102.37 (5.24)	103.25 (5.29)
60cm-90cm	93.80 (8.82)	104.06 (8.09)	105.83 (4.79)
90cm-120cm	94.05 (7.05)	98.88 (2.88)	97.30 (1.91)
Zone mean	94.94	101.77	102.13
F value	5.04^{ns} (Zones)		0.84^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The slenderness ratio was recorded the highest for 60 cm -90 cm *i.e.* 104.06 which belongs to midland and the lowest value *i.e.* 93.80 observed from 60 cm -90 cm which belongs to lowland. The maximum zonal mean value was observed for highland *i.e.* 102.13 and the lowest zonal mean value (94.94) for lowland. There was no significant variation observed between the zones and for girth classes within zones.

4.3.1.4) Shape factor and FL-FD ratio

Fibers with lower values of shape factor will give better strength to paper and lower tensile stiffness (Page and Seth, 1980). So, species with lower shape factor is suitable as a raw material for pulping and paper making. Shape factor and solid factor were found to be related to the paper sheet density and could significantly be correlated to breaking length of paper in Eucalyptus (Ona *et al.,* 2001). According to Page and Seth (1980), lower the value of shape factor, higher will be the paper strength.

Table 27 shows the value for shape factor, the highest shape factor was recorded for midland *i.e.* 0.52 which belongs to 30 cm -60 cm girth class and the 90 cm -120 cm of midland observed lowest value of 0.34. The highest zonal mean value was noticed for midland *i.e.* 0.45 and the lowest zonal mean value of 0.41 for the wood procured from lowland. The FL-FD ratio for wood procured from the different zones gave the highest value of 52.03 for 60 cm -90 cm which belongs to midland and the lowest value *i.e.* 46.90 for the wood procured from lowland which belongs to 60 cm -90 cm girth class (Table 28). The maximum zonal mean value of 51.06 was observed for highland and the minimum zonal mean value of 47.47 for lowland. There was no significant variation observed between the zones and for girth classes within zones for both shape factor and FL-FD ratio.

Table 27. Variation in shape factor of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	0.42 (0.04)	0.52 (0.06)	0.39 (0.04)
60cm-90cm	0.38 (0.03)	0.49 (0.06)	0.44 (0.05)
90cm-120cm	0.42 (0.11)	0.34 (0.02)	0.47 (0.03)
Zone mean	0.41	0.45	0.43
F value	0.75^{ns} (Zones)		1.45^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 28. Variation in FL-FD ratio of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	48.49 (2.75)	51.18 (2.02)	51.62 (2.64)
60cm-90cm	46.90 (4.41)	52.03 (4.04)	52.92 (2.39)
90cm-120cm	47.03 (3.52)	49.44 (1.44)	48.65 (0.96)
Zone mean	47.47	50.88	51.06
F value	5.04^{ns} (Zones)		0.84^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.3.2) Vessel morphology

4.3.2.1) Vessel diameter and Vessel area

Vessels are thin walled and relatively large diameter (varies 50 µm -300µm) cells with function of sap conduction in trees. They are present in all broad-leaved species and elements are stacked longitudinally end to end to form vessels. Table 29 gives the data for vessel diameter for the wood samples procured from the different zones. The highest vessel diameter was recorded *i.e.* 221.13 µm which belongs to 90 cm -120 cm girth class from midland and the lowest of 203.79 µm for highland which belongs to 60 cm -90 cm girth class.

Table 29. Variation in vessel diameter (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	214.41 (10.68)	212.60 (1.61)	216.43 (19.95)
60cm-90cm	204.19 (5.42)	217.42 (1.73)	203.79 (7.62)
90cm-120cm	220.78 (12.28)	221.13 (5.84)	211.11 (10.75)
Zone mean	213.13	217.05	210.44
F value	0.25^{ns} (Zones)		1.45^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The highest zonal mean value obtained from midland *i.e.* 217.05 µm and the lowest zonal mean value (210.44 µm) for highland. There was no significant variation observed between the zones and for girth classes within zones. In the Table 30, the data for vessel area was recorded the highest *i.e.* 29291.47 µm^2 for 90 cm -120 cm girth class which belongs to midland and the lowest for highland *i.e.* 24630.26 µm^2 which belongs to 60 cm -90 cm girth class. The highest zonal mean value of 26722.03 µm^2 was observed for midland and the lowest zonal mean value for highland *i.e.*

26270.21 µm^2. There was no significant variation observed between the zones and for girth classes within zones

Table 30. Variation in vessel area (µm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	25477.35 (1758.27)	25848.88 (2213.81)	27152.11 (3159.88)
60cm-90cm	25888.89 (1201.85)	25025.74 (1272.72)	24630.26 (1604.92)
90cm-120cm	27480.33 (2888.13)	29291.47 (653.19)	27028.27 (3422.67)
Zone mean	26282.19	26722.03	26270.21
F value	0.07 ^{ns} (Zones)		1.67 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.3.2.2) Vessel length and Vessel frequency

The Table 31 shows the data for vessel length obtained from the observations made through microanatomical studies. The maximum value of 245.36 µm was recorded for 30 cm -60 cm which belongs to highland and the minimum *i.e.* 226.57 µm observed for midland which was of 90 cm -120 cm girth class (Fig. 7). The highest zonal mean value of 240.92 µm was recorded for highland and the lowest zonal mean value for midland *i.e.* 232.94 µm. There was no significant variation observed between the zones but variation was observed for girth classes within zones.

Table 31. Variation in vessel length (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	237.41 ^{A} (3.78)	241.03 ^{A} (8.08)	245.36 ^{A} (3.14)
60cm-90cm	244.31 ^{A} (3.70)	231.23 ^{AB} (3.44)	234.88 ^{A} (6.63)
90cm-120cm	238.65 ^{A} (7.57)	226.57 ^{B} (2.09)	242.51 ^{A} (8.47)
Zone mean	240.12 ^{a}	232.94 ^{a}	240.92 ^{a}
F value	1.78 ^{ns} (Zones)	2.99* (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 32. Variation in vessel frequency (no. / mm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	5.00 (0.17)	4.93 (0.33)	4.82 (0.56)
60cm-90cm	5.00 (0.13)	5.00 (0.13)	4.73 (0.43)
90cm-120cm	5.00 (0.14)	5.00 (0.41)	5.44 (0.23)
Zone mean	5.00	4.98	4.98
F value	0.25 ^{ns} (Zones)	1.33 ^{ns} (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

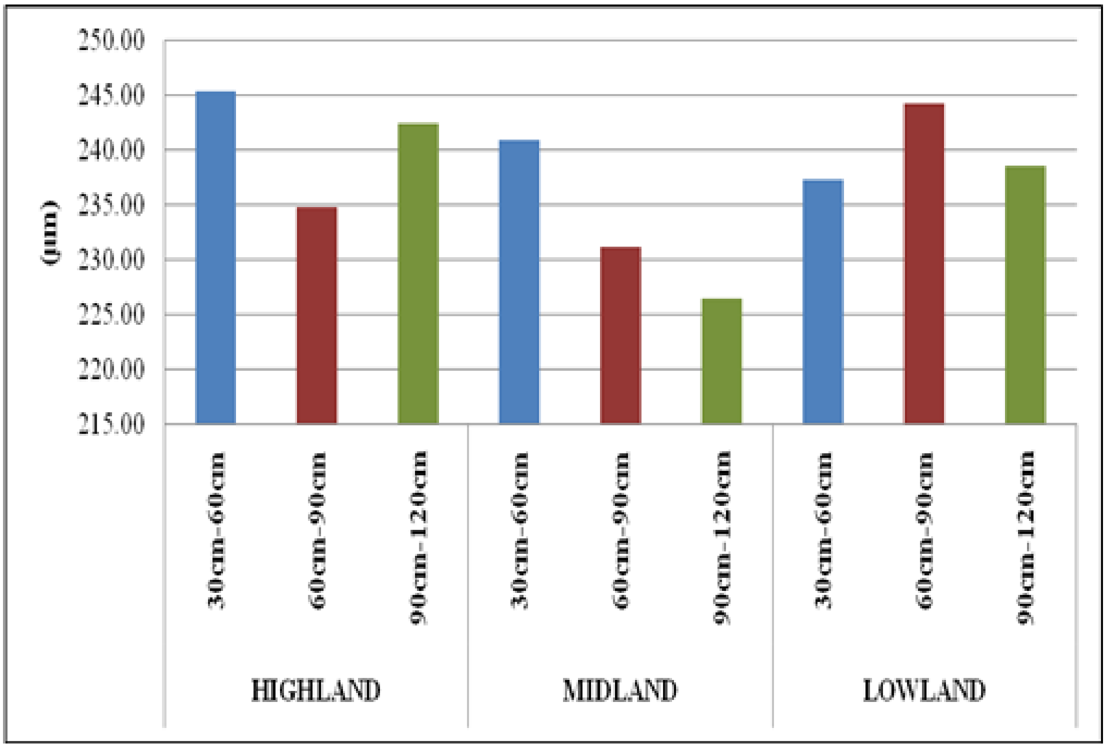

Fig. 7. Vessel Length (µm) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

Table 32 shows the values for vessel frequency in which the highland showed the highest mean value *i.e.* 5.44 which belongs to 90 cm -120 cm girth class and the lowest value of 4.73 which belongs to 60 cm -90 cm girth class from highland. The highest zone mean value was observed for lowland *i.e.* 5 and the lowest zonal mean value for both midland and highland *i.e.* 4.98. There was no significant variation observed between the zones and for girth classes within zones.

4.3.2.3) Ecoanatomical properties of *Artocarpus heterophyllus* wood

4.3.2.3.1) Vulnerability index

4.3.2.3.2) Vessel mesomorphy

With regard to ecological effects on wood anatomy in woody perennials and also in entire floras, a vast area has been covered by Carlquist (2001) and Baas *et al.* (2004). Carlquist (1977) determined two indices *i.e.* Vulnerability and Mesomorphy for determining the role of ecological factors in variation in wood anatomy. Mesomorphy is considered as the measure of availability of water to the species (Carlquist, 2009) and the values of both vary according to different climatic conditions.

Table 33. Variation in vulnerability index of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	42.99 (2.44)	43.23 (3.10)	45.40 (7.62)
60cm-90cm	43.35 (0.12)	43.50 (0.82)	43.34 (4.74)
90cm-120cm	44.53 (0.67)	46.26 (3.65)	38.77 (0.84)
Zone mean	43.62	44.33	42.50
F value	0.28 ^{ns} (Zones)		1.29 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 34. Variation in vessel mesomorphy of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	10200.84 (447.67)	10423.99 (872.12)	11145.42 (1928.74)
60cm-90cm	10589.84 (159.45)	10057.95 (197.89)	10175.60 (1106.83)
90cm-120cm	10630.56 (470.04)	10476.90 (745.03)	9402.18 (368.07)
Zone mean	10473.75	10319.61	10241.07
F value	0.22^{ns} (Zones)	1.13^{ns} (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The Table 33 revealed the data which shows the vulnerability index derived from the vessel morphology parameters. The maximum value of 46.26 was observed for midland which belongs to 90 cm -120 cm girth class and the minimum value of 38.77 was recorded for 90 cm -120 cm girth class wood which is from highland. The highest zone mean value of 44.33 was recorded for midland and the lowest zonal mean value for highland *i.e.* 42.50. There was no significant variation observed between the zones and for girth classes within zones.

Table 34 shows the data for vessel mesosmorphy in which the highest value *i.e.* 11145.42 obtained from highland wood which was of 30 cm -60 cm girth class and the lowest for 90 cm -120 cm girth class wood obtained from highland *i.e.* 9402.18. The highest zone mean value of 10473.75 was recorded for lowland and lowest zonal mean value for highland *i.e.* 10241.07. There was no significant variation observed between the zones and for girth classes within zones.

4.3.3) Ray morphology

4.3.3.1) Ray width, Ray height and Ray frequency

Radial parenchymatous rays facilitate flow in radial direction in trees and helps in identification as their width and height range widely. Ray height refers to length of ray end in longitudinal direction, whereas ray width refers to the number of ray cells in a row in the tangential direction at the ray's widest point. Variations have been noticed in its dimensions (length and width) and also in frequency among different toon provenances. The parameters are affected by both genetic and environmental factors.

Table 35. Variation in ray width (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	38.44^{A} (2.10)	45.24^{A} (1.21)	45.96^{C} (0.68)
60cm-90cm	44.58^{B} (1.27)	44.73^{A} (0.46)	36.13^{A} (0.08)
90cm-120cm	45.17^{B} (0.85)	44.91^{A} (0.91)	37.43^{B} (0.74)
Zone mean	42.73^{a}	44.96^{a}	39.84^{a}
F value	1.39^{ns} (Zones)	36.98* (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The data in the Table 35, Table 36 and Table 37 shows the ray width, ray height and ray frequency respectively which was obtained from the micranatomical studies. The results reveal that the highest ray width was recorded for highland wood *i.e.* 45.96 µm which belongs to 30 cm -60 cm girth class and the lowest ray width again for highland *i.e.* 36.13 µm which belongs to 60 cm -90 cm girth class of highland (Fig. 8). The highest zone mean value of 44.96 µm was recorded

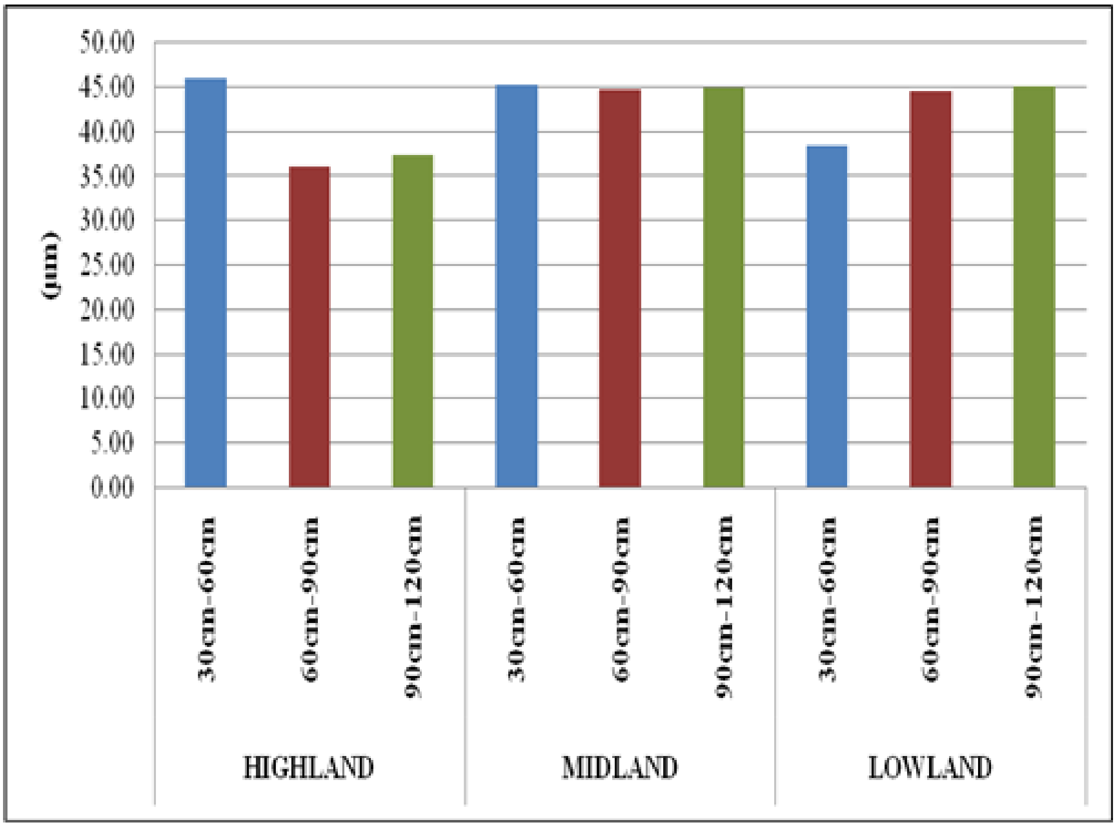

Fig.8. Ray Width (µm) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

Table 36. Variation in ray height (µm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	408.83 (14.54)	444.52 (10.26)	412.84 (9.39)
60cm-90cm	418.47 (10.10)	444.83 (13.68)	432.32 (51.33)
90cm-120cm	424.60 (23.90)	427.33 (11.15)	472.81 (8.43)
Zone mean	417.30 [a]	438.89 [a]	439.32 [a]
F value	1.29 [ns] (Zones)	2.41 [ns] (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 37. Variation in ray frequency (no. / mm) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	5.27 (0.40)	5.00 (0.12)	5.00 (0.23)
60cm-90cm	5.00 (0.08)	5.00 (0.06)	5.00 (0.27)
90cm-120cm	5.00 (0.33)	5.00 (0.30)	5.00 (0.25)
Zone mean	5.09 [a]	5.00 [a]	5.00 [a]
F value	1.00 [ns] (Zones)	1.00 [ns] (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

for midland and the lowest zonal mean value 39.84 µm was recorded for highland. There was no significant variation observed between the zones but variation was observed for girth classes within zones. The studies on ray height in table 35 observed highest value of 472.81 µm for 90 cm -120 cm girth class wood obtained from highland and the lowest ray height of 408.83 µm for 30 cm -60 cm girth class wood which belongs to high land. The maximum zonal mean value of 439.32 µm was recorded for highland and the lowest zonal mean value of 417.30 µm for lowland. There was no significant variation observed between the zones and for girth classes within zones. The ray frequency values given in table 36 shows the same number for lowland, midland and high land *i.e.* 5 for all girth classes. There was no significant variation observed between the zones and for girth classes within zones.

4.3.4) Tissue proportion

4.3.4.1) Vessel (%), Parenchyma (%), Fibre (%) and Ray (%)

The table 38, table 39, table 40 and table 41 shows the amount of individual cellular components vessels, parenchyma, fibres and rays respectively which were present inside the wood that helps in their strength and durability which in turn gives the different species of wood the nature of versatile utility. The vessel per cent was recorded the highest for wood which was procured from highland *i.e.* 2.92% which belongs to 90 cm -120 cm girth class and the lowest for 90 cm -120 cm girth class wood from lowland *i.e.* 1.88%. The highest zone mean value of 2.55% was for highland wood and the lowest zonal mean value for lowland wood *i.e.* 2.16%. There was no significant variation observed between the zones and girth classes within zones.

Table 38. Variation in vessel (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	2.33 (1.52)	2.31 (1.50)	2.81 (1.67)
60cm-90cm	2.27 (1.51)	2.81 (1.67)	1.94 (1.39)
90cm-120cm	1.88 (1.37)	2.36 (1.53)	2.92 (1.71)
Zone mean	2.16	2.49	2.55
F value	0.85^{ns} (Zones)	2.63^{ns} (Girth classes within zones)	

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 39. Variation in parenchyma (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	35.67 (5.97)	38.22 (6.12)	39.11 (6.23)
60cm-90cm	33.50 (5.782)	40.15 (6.33)	33.96 (5.81)
90cm-120cm	32.27 (5.68)	31.48 (5.61)	32.32 (5.68)
Zone mean	33.81	36.62	35.13
F value	0.42^{ns} (Zones)	1.09^{ns} (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 40. Variation in fibre (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	51.28 (7.16)	49.55 (6.99)	49.75 (7.03)
60cm-90cm	54.65 (7.39)	49.88 (7.06)	55.86 (7.47)
90cm-120cm	58.53 (7.65)	58.68 (7.66)	55.53 (7.45)
Zone mean	54.82	52.70	53.71
F value	0.04^{ns} (Zones)		1.30^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 41. Variation in ray (%) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	10.71^{B} (3.27)	9.91^{B} (3.14)	10.85^{B} (3.29)
60cm-90cm	9.57^{B} (3.09)	10.05^{B} (3.17)	8.22^{A} (2.87)
90cm-120cm	8.56^{A} (2.69)	7.47^{A} (2.73)	9.21^{AB} (3.03)
Zone mean	9.61	9.14	9.43
F value	0.24^{ns} (Zones)		7.41* (Girth classes within zones)

- *Value in parenthesis is square root transformed value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

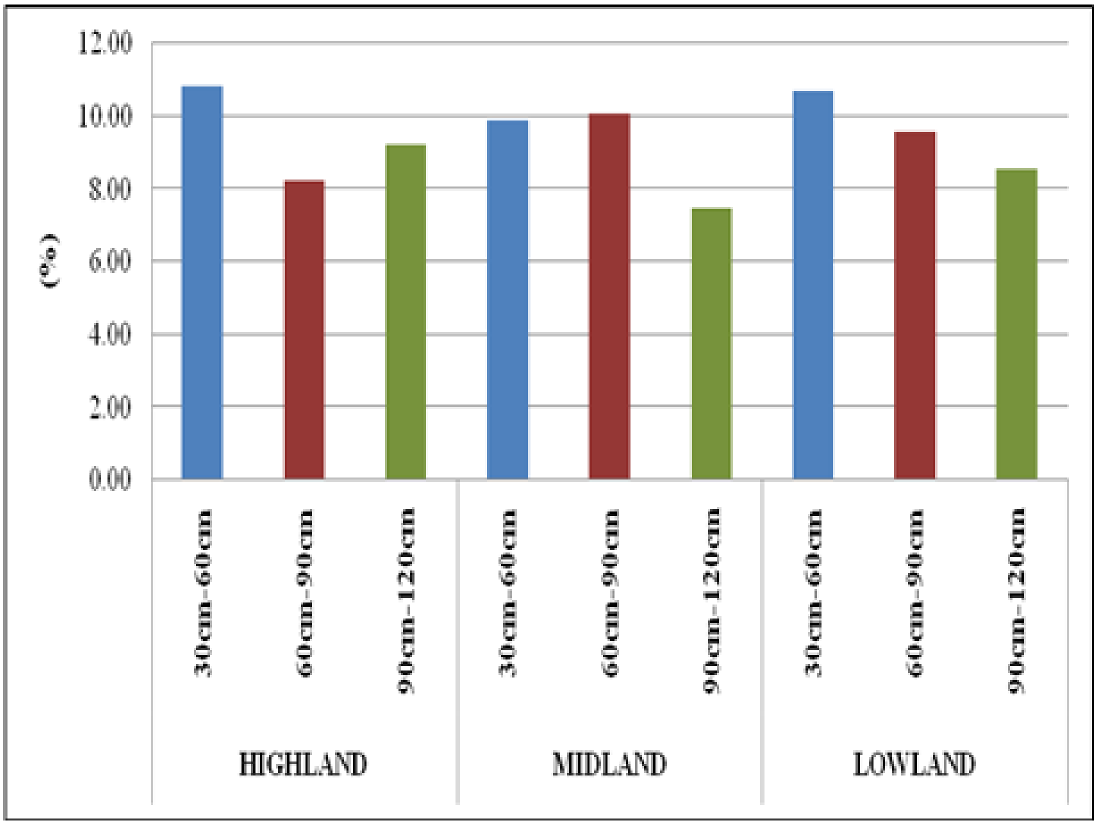

Fig. 9. Ray (%) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

The table on parenchyma per cent revealed that the highest value of 36.62 % was observed for midland which belongs to 60 cm -90 cm girth class and the lowest for midland *i.e.* 31.48% which belongs to 90 cm -120 cm girth class. The maximum zone mean value was recorded for midland *i.e.* 36.62% and the lowest zonal mean value of 33.81% for lowland. There was no significant variation observed between the zones and for girth classes within zones.

The fibre per cent was recorded the maximum for 90 cm -120 cm girth class which belongs to midland *i.e.* 58.68% and the minimum of 49.55% for 30 cm -60 cm girth class wood from midland. The highest zonal mean values of fibres were recorded from lowland *i.e.* 54.82% and the lowest zonal mean value for midland *i.e.* 52.70%. There was no significant variation observed between the zones and for girth classes within zones. The table on ray per cent shows the highest value *i.e.* 10.85% obtained from highland which belongs to 30 cm -60 cm girth class and the lowest value of 7.47% from 90 cm -120 cm girth class which belongs to midland (Fig. 9). The highest zonal mean value was obtained from lowland *i.e.* 9.61% and the lowest zonal mean value of 9.14 from midland. There was no significant variation observed between the zones but variation was observed for girth classes within zones.

4.4) MECHANICAL PROPERTIES OF WOOD

4.4.1) Static bending test

4.4.1.1) Modulus of Rupture and Maximum Load

Modulus of Rupture (MOR) is a measure of a specimen's strength before rupture. It can be used to determine overall strength of wood species; unlike the Modulus of Elasticity, which measures the deflection of wood, but not its ultimate strength. Table 42 shows the data for modulus of rupture which was recorded. The maximum MOR of 923.79 kg/cm^2 was observed for 60 cm -90 cm girth class and the minimum MOR of 467.62 kg/cm^2 for lowland which belongs to 60 cm -90 cm girth class (Figure 40). The highest zonal mean value of 759.82 kg/cm^2 was observed for midland and the lowest zonal mean value for highland *i.e.* 513.29 kg/cm^2. There was no significant variation observed between the zones and for girth classes within zones.

Table 42. Variation in Modulus of Rupture (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	574.09 (145.15)	572.87 (193.04)	599.40 (312.94)
60cm-90cm	467.62 (127.45)	923.79 (103.34)	826.89 (308.20)
90cm-120cm	498.15 (179.39)	782.82 (154.28)	832.26 (259.18)
Zone mean	513.29	759.82	752.85
F value	2.63^{ns} (Zones)		1.24^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 43. Variation in Maximum Load (kg) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	116.12 (16.65)	119.03 (21.78)	114.22 (59.44)
60cm-90cm	105.35 (9.30)	176.59 (19.57)	158.00 (58.92)
90cm-120cm	114.31 (15.27)	155.87 (18.22)	158.90 (49.74)
Zone mean	111.93	150.50	143.71
F value	2.62^{ns} (Zones)		1.26^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The data in table 43 which shows the maximum load that has been taken for the wood samples to cause the rupture in which the maximum value was observed for midland *i.e.* 176.59 kg which belongs to 60 cm -90 cm and the minimum value of 105.35 kg for 60 cm -90 cm girth class wood from lowland (Figure 41). The highest zonal mean value of maximum load was observed for midland *i.e.* 150.50 kg and lowest zonal mean value of 111.93 kg recorded for lowland. There was no significant variation observed between the zones and for girth classes within zones.

4.4.1.2) Horizontal Stress at Maximum Load and Horizontal Stress at Limit of Proportionality

In table 44 which recorded the HS at ML, the highest value of 33.03 kg/cm^2 was recorded for girth class of 60 cm -90 cm which belongs to midland zone and the lowest value was observed for wood procured from lowland *i.e.* 17.89 kg/cm^2 which belongs to the 60 cm -90cm girth class (Figure 42).

Table 44. Variation in HS at ML (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	21.72 (3.13)	20.45 (6.92)	21.40 (11.15)
60cm-90cm	17.89 (4.84)	33.03 (3.68)	29.56 (11.03)
90cm-120cm	18.96 (7.16)	29.17 (3.44)	29.74 (9.27)
Zone mean	19.52	27.55	26.90
F value	2.62^{ns} (Zones)		1.25^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The maximum zonal mean value of 27.55 kg/cm^2 was observed for midland and the minimum zonal mean value for lowland *i.e.* 19.52 kg/cm^2. There was no significant variation observed between the zones and for girth classes within zones. The table 45 shows the HS at LP data recorded for the wood samples collected from different zones. The highest value of 20.10 kg/cm^2 was observed for 60-90 cm girth class (Figure 43) which belonged to highland and the lowest value was recorded for 30-60 cm girth class which belonged to lowland zone *i.e.* 14.75 kg/cm^2. The maximum zonal mean value of 18.48 kg/cm^2 was recorded for highland and the lowest zonal mean value of 15.33 kg/cm^2 for lowland. There was no significant variation observed between the zones and for girth classes within zones.

Table 45. Variation in HS at LP (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	14.75 (4.09)	16.29 (1.51)	17.00 (9.86)
60cm-90cm	15.74 (2.17)	19.50 (0.88)	20.10 (10.28)
90cm-120cm	15.50 (1.52)	18.59 (0.62)	18.34 (5.14)
Zone mean	15.33	18.13	18.48
F value	4.07 ^{ns} (Zones)	0.45 ^{ns} (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.4.1.3) Fibre Stress at Limit of Proportionality and Bending Modulus of Elasticity

Bending strength of wood revealed its capacity to use as a beam or similar types of constructional uses. The variations noticed in the bending strength of different wood species from different locations may be due to the presence of knots, cellular compositions, cell wall depositions, extractives and even the variable growth parameters. The table 46 shows the data for FS at LP for which the highest value was observed for wood samples from highland *i.e.* 562.19 kg/cm^2 belong to 60 cm-90 cm girth class and the lowest *i.e.* 412.55 kg/cm^2 for girth class of 30 cm-60 cm from lowland zone (Figure 44). The highest zonal mean value of 517.16 kg/cm^2 was observed for highland and the lowest zonal mean value for lowland *i.e.* 422.54 kg/cm^2. There was no significant variation observed between the zones and for girth classes within zones.

Table 46. Variation in FS at LP (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	412.55 (114.82)	462.81 (45.49)	476.24 (276.41)
60cm-90cm	414.21 (100.99)	545.32 (24.73)	562.19 (287.62)
90cm-120cm	440.87 (184.94)	520.19 (17.59)	513.06 (143.66)
Zone mean	422.54	509.44	517.16
F value	4.10 ^{ns} (Zones)		0.45 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 47. Variation in MOEB (kg/cm²) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	57423.41 (10555.17)	48165.96 (14953.69)	62277.93 (19880.40)
60cm-90cm	48262.93 (13848.76)	80653.92 (7726.32)	69379.70 (27971.89)
90cm-120cm	54456.70 (22214.63)	68913.96 (5324.22)	68490.50 (16637.24)
Zone mean	53381.01	65911.28	66716.04
F value	1.63^{ns} (Zones)	1.08^{ns} (Girth classes within zones)	

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

The highest value for MOEB was recorded for 60 cm -90 cm girth class of wood *i.e.* 80653.92 kg/cm² from midland and the lowest value of 48165.96 kg/cm² was observed for 30 cm -60 cm girth class from midland (Figure 45). The highest zonal mean value of 66716.04 kg/cm² was observed for highland and the lowest zonal mean value for lowland *i.e.* 53381.01 kg/cm² (Table 47). There was no significant variation observed between the zones and for girth classes within zones.

4.4.2) Tensile Strength at Maximum Load

Tensile strength is the ability of any material to resist the stretching forces when external forces act on a piece of timber in a direction away from its end or such that the fibres are pulled apart, the timber is said to be subjected to tensile stresses. However, study of this parameter provides an idea about working of the wooden sample when subjected under such forces. Woods when used for construction and other purposes are subjected to such type of forces. The table 48 shows the data of TS at ML in which the highest value was recorded for highland *i.e.* 883.85 kg/cm² which belongs to the girth class of 90 cm -120 cm and the lowest value of 537.86 kg/cm² for highland which belongs to 30 cm -60 cm girth class (Figure 46). The highest zonal mean value of 744.76 kg/cm^2 which was recorded for midland and the lowest zonal mean value for lowland *i.e.* 649.05 kg/cm^2. The present study indicates non-significant results for tensile strength of wood samples collected from different sites.

Table 48. Variation in TS at ML (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	662.33 (237.34)	665.74 (204.56)	537.86 (95.59)
60cm-90cm	607.20 (189.19)	873.46 (287.51)	646.05 (99.45)
90cm-120cm	677.63 (312.82)	695.08 (63.43)	883.85 (135.50)
Zone mean	649.05	744.76	689.25
F value	0.53 ^{ns} (Zones)		1.43 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.4.3) Compression strength Parallel to grain

4.4.3.1) Compression strength Parallel to grain at Limit of Proportionality and at Maximum Load

Wood is an important raw material used for different multiple applications and may be subjected to compressive forces during its use. Hence, determination of maximum compressive stress bearing ability is an important factor for its end use. Compression of wood with application of compressive forces varies with the wood porosity and cellular composition.

Even the presence of extractives and lignin depositions also influence the compressive strength of wood. If wood is considered as a bundle of straws bound together, then a compression parallel to grain can be thought of as a force trying to compress the straws from end to end (Rowell, 2013). Generally, the wood is strongest in parallel to grain because cells are aligned in this direction. The table 49 shows the CSPL at LP data of wood procured from the different zones for which the highest value was recorded for 60 cm -90 cm girth class *i.e.* 388.45 kg/cm^2 of midland zone and the lowest for highland *i.e.* 243.90 kg/cm^2 which belongs to 30 cm -60 cm girth class (Figure 47). The highest zonal mean value of 332.65 kg/cm^2 was observed for midland and the lowest zonal mean value of 298.83 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones.

Table 49. Variation in CSPL at LP (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	245.22 (63.50)	250.15 (107.27)	243.90 (27.34)
60cm-90cm	295.55 (23.02)	388.45 (99.74)	310.51 (116.18)
90cm-120cm	366.67 (61.39)	359.36 (10.27)	342.08 (83.18)
Zone mean	302.48	332.65	298.83
F value	0.64 ^{ns} (Zones)		1.41 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 50 revealed the data which shows the highest value of CSPL at ML for midland *i.e.* 514.75 kg/cm^2 which belongs to 60 cm -90 cm girth class and the lowest value for midland which comes under 30 cm -60 cm girth class *i.e.* 350.95 kg/cm^2 (Figure 48). The highest zonal mean value of 449.31 kg/cm^2 was observed for midland and the lowest zonal mean value *i.e.* 410.54

kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones.

Table 50. Variation in CSPL at ML (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	379.93 (24.16)	350.95 (118.33)	367.35 (24.98)
60cm-90cm	401.73 (19.07)	514.75 (95.10)	420.90 (122.17)
90cm-120cm	459.72 (64.11)	482.22 (17.00)	443.38 (98.56)
Zone mean	413.79	449.31	410.54
F value	1.00 ^{ns} (Zones)		1.31 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.4.3.2) Modulus of Elasticity for Compression parallel to grain (kg/cm^2)

Modulus of Elasticity (MOE) measures a stiffness of wood, and is a good overall indicator of its strength. It is the ratio of stress placed upon the wood compared to the strain (deformation) that the wood exhibits along its length. Elasticity of any material determines its level of retention of original size and shape. Hence, determination of wood elasticity has got great significance in finding its suitability for specific uses. The variations in the mechanical properties of wood from different sites can be due to various factors such as growth conditions and ecological factors. The altitude, soil, and climatic conditions can affect the mechanical properties of wood (Bektas *et al.*, 2002).

The highest value for MOECSPL was observed for midland *i.e.* 39421.74 kg/cm^2 (Figure 49) which belongs to 60 cm -90 cm girth class of wood and the lowest value of 24628.42 kg/cm^2 was recorded for midland with comes under 30 cm -60 cm girth class (Table 51). The highest zonal mean of 35852.52 kg/cm^2 was observed for midland and lowest zonal mean value of 31534.68 kg/cm^2 for lowland. There was no significant variation observed between the zones and for girth classes within zones.

Table 51. Variation in MOE (CSPL) (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	26005.11 (5322.28)	24628.42 (8019.04)	35328.20 (4605.81)
60cm-90cm	30826.73 (8025.88)	39421.74 (3405.12)	28561.36 (14895.55)
90cm-120cm	37772.21 (1864.27)	34507.41 (5823.75)	35662.67 (12624.25)
Zone mean	31534.68	35852.52	33184.08
F value	0.51^{ns} (Zones)		1.09^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.4.4) Compression strength Perpendicular to grain

4.4.4.1) Compression strength Perpendicular to grain at Limit of Proportionality (kg/cm^2) and at 2.5mm (kg/cm^2)

Compression perpendicular to grain is the force applied perpendicular to the length of wood cells (Rowell, 2013). When a load applied perpendicular to the cells (grains), the thin walled tubes are affected laterally and is squeezed together with the increase of compression stresses and start to collapse. This behaviour continues until all the fibers are fully crushed. When all fibers are crushed together it is possible to once again increase the loads and it is difficult to define a failure level as the wood gets compressed.

The table 52 shows the data for CSPR at LP in which the maximum value of 149.23 kg/cm^2 was observed for midland which belongs to the girth class of 60 cm -90 cm and the lowest value of 92.86 kg/cm^2 for lowland which belongs to 60 cm -90cm girth class of wood (Figure 50). The maximum zonal value of 130.82 kg/cm^2 was observed for midland and the minimum value of 103.12 kg/cm^2 for lowland zone. There was no significant variation observed between the zones and for girth classes within zones.

Table 52. Variation in CSPR at LP (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	111.49 (22.80)	124.19 (7.95)	92.90 (5.36)
60cm-90cm	92.86 (19.24)	149.23 (76.44)	121.86 (17.82)
90cm-120cm	105.01 (12.58)	119.04 (28.88)	102.07 (9.74)
Zone mean	103.12	130.82	105.61
F value	3.09^{ns} (Zones)		0.78^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

Table 53 reveals the highest value of CSPR at 2.5mm *i.e.* 251.31 kg/cm^2 for wood procured from midland which belongs to the girth class of 60 cm -90 cm and the lowest value of 128.97 kg/cm^2 for 60 cm -90 cm girth class which belongs to the lowland zone (Figure 51). The highest zonal mean value was observed for midland *i.e.* 233.75 kg/cm^2 and the lowest zonal mean value of 170.52 kg/cm^2 for lowland. There was no significant variation observed between the zones and for girth classes within zones.

Table 53. Variation in CSPR at 2.5mm (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	**Midland**	**Highland**
30cm-60cm	190.83 (30.49)	231.86 (21.87)	165.59 (25.49)
60cm-90cm	128.97 (43.96)	251.31 (125.26)	210.82 (27.08)
90cm-120cm	191.76 (36.41)	218.08 (47.34)	171.30 (27.15)
Zone mean	170.52	233.75	182.57
F value	3.00 ^{ns} (Zones)		1.36 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.4.4.2) Modulus of Elasticity for Compression Perpendicular to grain (kg/cm^2)

Modulus of Elasticity perpendicular to grain has shown variation in different species from different locations which can be due to the variable cellular composition because of which the Modulus of Elasticity is different for all the species. The table 54 shows the data for MOECSPR in which the highest value of 26012.12 kg/cm^2 was observed for midland which belongs to 60 cm -90 cm girth class and the lowest value of 17410.08 kg/cm^2 for highland which belongs to the girth class of 30 cm -60 cm (Fig. 10). The maximum zonal mean value of 24287.43 kg/cm^2 was recorded for midland and the minimum zonal mean value of 13218.68 kg/cm^2 for highland. There was no significant variation observed between the zones but variation was observed for girth classes within zones.

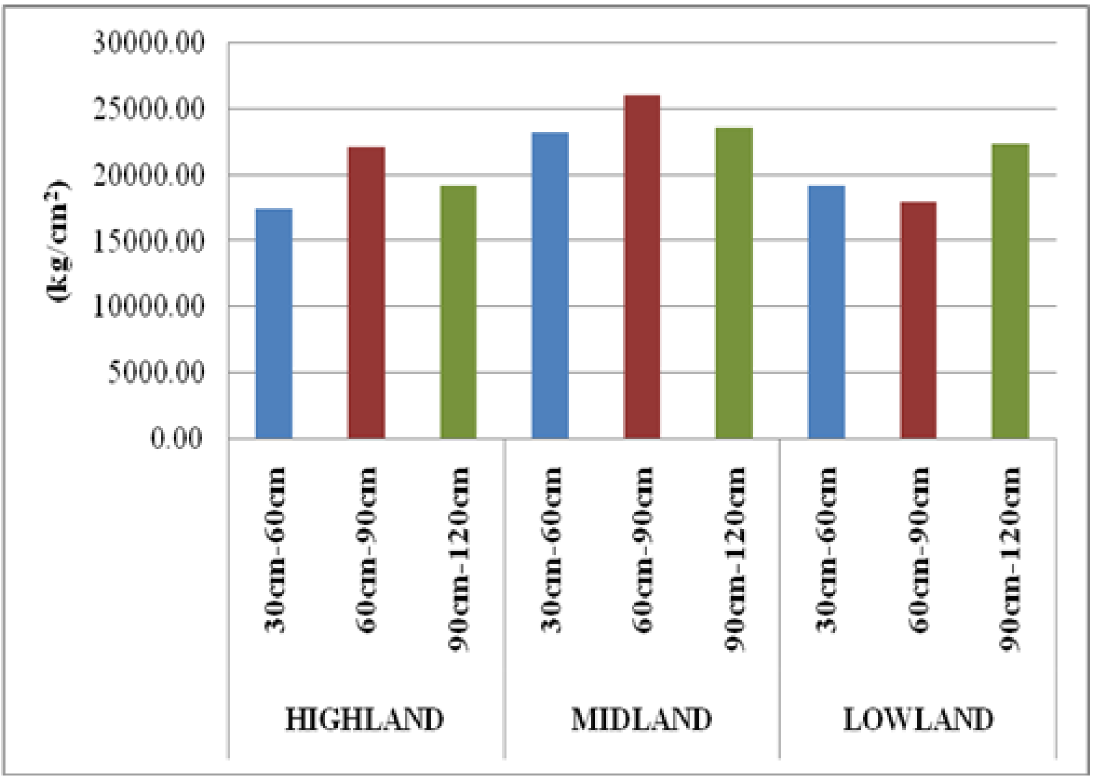

Fig. 10. Compression strength Perpendicular to grain at Modulus of Elasticity (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood in three different zones of different girth classes

Table 54. Variation in MOE (CSPR) (kg/cm^2) of *Artocarpus heterophyllus* Lam. wood from three different zones

Girth classes	Zones		
	Lowland	Midland	Highland
30cm-60cm	19135.35 (2050.15)	23221.65 (1283.28)	17410.08 (1949.64)
60cm-90cm	17996.12 (5829.14)	26012.12 (10370.58)	22074.66 (5569.36)
90cm-120cm	22340.02 (1693.48)	23628.53 (4205.14)	19173.89 (567.18)
Zone mean	19823.83 ^{a}	24287.43 ^{b}	13218.68 ^{ab}
F value	10.66* (Zones)		0.30 ^{ns} (Girth classes within zones)

- *Value in parenthesis is standard deviation value; (*) significant at 0.05 level; (ns) non significant at 0.05 level*

4.5) SIMPLE CORRELATION COEFFICIENTS

4.5.1) Simple correlation coefficients between physical and chemical properties of *Artocarpus heterophyllus* wood

The data pertaining to the correlation coefficient values between physical and chemical properties of *Artocarpus heterophyllus* are shown in Table 55. Out of total 153 combinations of simple correlation coefficients obtained between physical and chemical parameters, three were found to be positive and significant at 1% level of significance, three were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1% and one was reported as negatively correlated and significant at 5% level of significance.

The correlation coefficients for different parameters are presented below as follows:

i) L* value

L* value of the color component was found to be negatively correlated and significant with the color component a* value (-0.851**).

ii) a* value

a* value was found to have significant and positive correlation with ash content (0.861). The values of rest of the correlation coefficient were noticed to be non-significant.

iii) Volumetric shrinkage

Volumetric shrinkage was observed to be positive and significantly correlated with green specific gravity (0.707), tangential shrinkage (0.677) and radial shrinkage (0.817). Rests of the values for correlation coefficient were found to be non-significant.

iv) Green Specific Gravity

Green Specific Gravity elucidated negative and significant correlation with NaOH soluble extractives content (-0.778). Rest of the values for correlation coefficient were found to be non-significant.

v) Tangential Shrinkage

Tangential Shrinkage was found positive and significantly correlated with radial shrinkage (0.919). All the remaining correlation values were found to be non-significant with moisture content.

vi) Holocellulose content

Holocellulose content of wood revealed positive and significant relationship with hemicellulose content (0.673). For rest of the values the correlation coefficient values were non-significant.

4.5.2) Simple correlation coefficients between physical and anatomical properties of *Artocarpus heterophyllus* wood

The data pertaining to the correlation coefficient values between physical and anatomical properties of *Artocarpus heterophyllus* are shown in Table 56. Out of total 153 combinations of simple correlation coefficients obtained between physical and anatomical parameters, three were found to be positive and significant at 1% level of significance, three were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1% and one was reported as negatively correlated and significant at 5% level of significance.

The correlation coefficients for different parameters are presented below as follows:

i) L* value

L* value of the color component was found to be negatively correlated and significant with the color component a* value (-0.851**).

ii) Tangential Shrinkage

Tangential Shrinkage was found to have significant and negative correlation with fibre diameter (-0.737**). The values of rest of the correlation coefficient were noticed to be non-significant.

iii) Volumetric shrinkage

Volumetric shrinkage was observed to be positive and significantly correlated with green specific gravity (0.707), tangential shrinkage (0.677) and radial shrinkage (0.817). Rests of the values for correlation coefficient were found to be non-significant.

iv) Oven dry Specific Gravity

Oven dry Specific Gravity elucidated positive and significant correlation with vessel area (0.715) and ray width (0.812). Rest of the values for correlation coefficient were found to be non-significant.

Table 55. Simple correlation coefficients between physical and chemical properties of *Artocarpus heterophyllus* wood

	L*value	a*value	B*valu	MC	VS	GSG	OSG	TS	RS	CWS	HWS	ALBZ	LGN	HCE	CLE	HCLE	NaOH	Ash
L*value																		
a*value	**-.851****																	
b*value	.509	-.618																
MC	.410	-.200	.220															
VS	-.397	.209	.222	-.094														
GSG	-.393	.237	.273	-.557	**.707***													
OSG	-.305	.334	.059	-.135	.177	.239												
TS	-.419	.021	.020	-.434	**.677***	.662	.073											
RS	-.575	.231	-.130	-.399	**.817****	.649	.123	**.919****										
CWS	.186	-.037	-.091	.080	-.303	-.025	-.442	.005	-.257									
HWS	-.094	.418	-.440	-.010	-.051	.066	.121	-.018	-.071	.641								
ALBZ	.478	-.175	.091	.598	-.205	-.234	.185	-.311	-.322	.087	.227							
LGN	.077	-.362	.265	.211	.021	-.073	.343	.429	.219	-.034	-.204	.252						
HCE	.055	.085	-.338	-.006	.434	.205	-.131	.272	.429	.007	.434	.296	-.275					
CLE	.479	-.301	-.075	-.130	-.118	.060	-.022	.100	-.062	.489	.664	.344	.004	.566				
HCLE	-.365	.370	-.331	.110	.619	.188	-.134	.231	.562	-.431	-.084	.041	-.328	**.673***	-.229			
NaOH	.186	.095	-.342	.641	-.587	**-.778***	-.330	-.589	-.627	.508	.365	.263	-.055	-.162	.006	-.196		
Ash	-.663	**.861****	-.322	.065	.275	.308	.428	-.041	.170	-.137	.262	.216	-.207	.082	-.365	.425	.020	

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

*. Correlation is significant at the 0.05 level (2-tailed).

- **MC** - Moisture content
- **VS** - Volumetric shrinkage
- **GSG** - Green Specific gravity
- **OSG** - Oven dry specific gravity
- **TS** - Tangential shrinkage
- **RS** - Radial shrinkage
- **CWS** - Cold water solubility
- **HWS** - Hot water solubility
- **ALBZ** - Alcohol benzene extractives
- **LGN** - Klason lignin content
- **HCE** - Holocellulose content
- **CLE** - Cellulose content
- **HCLE** - Hemicellulose content
- **NaOH** - Sodium hydroxide solubility

Table 56. Simple correlation coefficients between physical and anatomical properties of *Artocarpus heterophyllus* wood

	L*value	a*value	b*value	MC	VS	GSG	OSG	TS	RS	FL	FD	VD	VA	VL	VF	RW	RH	RF
L*value																		
a*value	**-.851****																	
b*value	.509	-.618																
MC	.410	-.200	.220															
VS	-.397	.209	.222	-.094														
GSG	-.393	.237	.273	-.557	**.707***													
OSG	-.305	.334	.059	-.135	.177	.239												
TS	-.419	.021	.020	-.434	**.677***	.662	.073											
RS	-.575	.231	-.130	-.399	**.817****	.649	.123	**.919****										
FL	-.227	.444	-.503	-.077	-.086	-.270	.215	-.260	-.152									
FD	-.027	.312	-.259	.304	-.450	-.540	.455	**-.737***	-.540	.284								
VD	-.385	.320	.352	-.326	.578	.612	.367	.092	.283	-.003	.065							
VA	-.513	.578	.096	-.239	.049	.327	**.715***	-.155	-.090	.136	.459	.633						
VL	.307	-.177	-.441	-.247	-.650	-.488	.100	-.371	-.363	.267	.446	-.410	-.186					
VF	-.450	.619	-.549	-.159	-.210	.017	-.096	-.268	-.070	-.120	.414	.108	.289	.136				
RW	-.260	.254	.058	-.074	.539	.279	**.812****	.188	.382	.305	.315	.524	.406	.028	-.219			
RH	-.392	.536	-.535	-.332	.088	.412	-.214	.226	.272	-.071	-.222	-.101	-.031	-.030	.665	-.283		
RF	.125	-.425	.211	.028	-.170	-.320	-.507	-.086	-.071	-.391	-.052	.051	-.244	-.035	.015	-.388	-.435	
**. Correlation is significant at the 0.01 level (2-tailed).																		
*. Correlation is significant at the 0.05 level (2-tailed).																		

- **MC** - Moisture content
- **VS** - Volumetric shrinkage
- **GSG** - Green Specific gravity
- **OSG** - Oven dry specific gravity
- **TS** - Tangential shrinkage
- **RS** - Radial shrinkage
- **FL** - Fibre length
- **FD** - Fibre diameter
- **VD** - Vessel diameter
- **VA** - Vessel area
- **VL** - Vessel length
- **VF** - Vessel frequency
- **RW** - Ray width
- **RH** - Ray height
- **RF** - Ray frequency

v) Radial Shrinkage

Radial Shrinkage was found positive and significantly correlated with Tangential shrinkage (0.919). All the remaining correlation values were found to be non-significant with moisture content.

4.5.3) Simple correlation coefficients between physical and mechanical properties of *Artocarpus heterophyllus* wood

The data pertaining to the correlation coefficient values between physical and mechanical properties of *Artocarpus heterophyllus* are shown in Table 57. Out of total 210 combinations of simple correlation coefficients obtained between physical and mechanical parameters, twenty were found to be positive and significant at 1% level of significance, ten were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1%.

The correlation coefficients for different parameters are presented below as follows:

i) L* value

L* value of the color component was found to be negatively correlated and significant with the color component a* value (-0.851**).

ii) Volumetric shrinkage

Volumetric shrinkage was observed to be positive and significantly correlated with green specific gravity (0.707), tangential shrinkage (0.677), radial shrinkage (0.817), Compression strength perpendicular to grain at Limit of Proportionality (0.822), Compression strength perpendicular to grain at 2.5mm (0.842) and Modulus of Elasiticity for Compression strength perpendicular to grain (0.874). Rests of the values for correlation coefficient were found to be non-significant.

iii) Green Specific Gravity

Green Specific Gravity elucidated positive and significant correlation with Compression strength perpendicular to grain at 2.5mm (0.801) and Modulus of Elasiticity for Compression strength perpendicular to grain (0.763). Rest of the values for correlation coefficient were found to be non-significant.

iv) Tangential Shrinkage

Tangential Shrinkage was found positive and significantly correlated with radial shrinkage (0.919). All the remaining correlation values were found to be non-significant with moisture content.

v) Modulus of Rupture

Modulus of Rupture was found positive and significantly correlated with Horizontal stress at Maximum Load (0.996), Horizontal stress at Limit of Proportionality (0.911), Fibre Stress at Limit of Proportionality (0.920), Modulus of Elasticity Bending (0.934) and Tensile Strength at Maximum Load (0.697). All the remaining correlation values were found to be non-significant with moisture content.

vi) Horizontal stress at Maximum Load

Horizontal stress at Maximum Load was found positive and significantly correlated with Horizontal stress at Limit of Proportionality (0.896), Fibre Stress at Limit of Proportionality (0.902), Modulus of Elasticity Bending (0.940), Tensile Strength at Maximum Load (0.704) and Compression strength parallel to grain at Maximum Load (0.672). All the remaining correlation values were found to be non-significant with moisture content.

vii) Horizontal stress at Limit of Proportionality

Horizontal stress at Limit of Proportionality was found positive and significantly correlated with Fibre Stress at Limit of Proportionality (0.984), Modulus of Elasticity Bending (0.835) and Tensile Strength at Maximum Load (0.704). All the remaining correlation values were found to be non-significant with moisture content.

Table 57. Simple correlation coefficients between physical and mechanical properties of *Artocarpus heterophyllus* wood

	L*value	a*value	b* value	MC	VS	GSG	OSG	TS	RS	MOR	HS at ML	HSat LP	FSat LP	MOEB	TS at ML	CSPLat LP	CSPLat ML	MOECSPL	CSPR at LP	CSPR at 2.5mm	MOE CSPR
L*value																					
a*value	**-.851****																				
b*value	.509	-.618																			
MC	.410	-.200	.220																		
VS	-.397	.209	.222	-.094																	
GSG	-.393	.237	.273	-.557	**.707***																
OSG	-.305	.334	.059	-.135	.177	.239															
TS	-.419	.021	.020	-.434	**.677***	.662	.073														
RS	-.575	.231	-.130	-.399	**.817****	.649	.123	**.919****													
MOR	-.375	.456	-.226	-.026	.333	.337	-.467	.225	.235												
HS at ML	-.383	.464	-.186	.031	.340	.324	-.458	.198	.216	**.996****											
HS at LP	-.219	.368	-.158	.068	.259	.289	-.274	.213	.133	**.911****	**.896****										
FS at LP	-.225	.339	-.082	-.058	.318	.422	-.281	.276	.187	**.920****	**.902****	**.984****									
MOEB	-.270	.417	-.097	.088	.344	.239	-.435	.008	.080	**.934****	**.940****	**.835****	**.844****								
TS at ML	-.389	.523	-.350	-.028	.307	.339	-.414	.089	.273	**.697***	**.704***	.450	.469	.606							
CSPL at LP	-.127	.431	.139	.391	.391	.352	.015	-.145	-.009	.543	.583	.514	.507	.592	**.674***						
CSPL at ML	-.199	.451	.143	.422	.461	.309	-.068	-.129	.033	.626	**.672***	.551	.541	**.714***	**.672***	**.968****					
MOECSPL	-.131	.536	-.054	.169	.232	.165	.185	-.445	-.206	.357	.371	.338	.337	.562	.433	**.751***	**.755***				
CSPR at LP	-.216	.043	.155	.025	**.822****	.574	-.355	**.670***	**.712***	.648	.648	.537	.583	.575	.537	.423	.502	.067			
CSPR at 2.5mm	-.262	.022	.303	-.255	**.842****	**.801****	-.206	**.758***	**.747***	.570	.564	.468	.567	.494	.420	.333	.393	.029	**.929****		
MOECSPR	-.214	.110	.341	.031	**.874****	**.763***	-.029	.633	.664	.520	.533	.483	.544	.454	.487	.616	.627	.216	**.903****	**.908****	

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

*. Correlation is significant at the 0.05 level (2-tailed).

- **MC** - Moisture content
- **VS** - Volumetric shrinkage
- **GSG** - Green Specific gravity
- **OSG** - Oven dry specific gravity
- **TS** - Tangential shrinkage
- **RS** - Radial shrinkage
- **MOR** - Modulus of Rupture
- **HS at ML** - Horizontal Stress at Maximum Load
- **CSPR at ML** **-** Compression perpendicular to grain at Maximum Load
- **HS at LP** - Horizontal Stress at Limit of Proportionality
- **FS at LP** - Fibre Stress at Limit of Proportionality
- **MOEB** - Modulus of Elasticity Bending
- **TS at ML** - Tensile Strength at Maximum Load
- **CSPL at LP** - Compression parallel to grain at Limit of Proportionality
- **CSPL at ML** - Compression parallel to grain at Maximum Load
- **MOE CSLP** **-** Modulus of Elasticity Compression parallel to grain
- **MOE CSPR** **-** Modulus of Elasticity Compression perpendicular to grain
- **CSPR at LP** **-** Compression perpendicular to grain at Limit of Proportionality

viii) Fibre Stress at Limit of Proportionality

Fibre Stress at Limit of Proportionality was found positive and significantly correlated with Modulus of Elasticity Bending (0.844). All the remaining correlation values were found to be non-significant with moisture content.

ix) Modulus of Elasticity Bending

Modulus of Elasticity Bending was found positive and significantly correlated with Compression strength parallel to grain at Maximum Load (0.714). All the remaining correlation values were found to be non-significant with moisture content.

x) Tensile Strength at Maximum Load

Tensile Strength at Maximum Load was found positive and significantly correlated with Compression strength parallel to grain at Maximum Load (0.672) and Compression strength parallel to grain at Limit of Proportionality (0.674). All the remaining correlation values were found to be non-significant with moisture content.

xi) Compression strength parallel to grain at Limit of Proportionality

Compression strength parallel to grain at Limit of Proportionality was found positive and significantly correlated to Compression strength parallel to grain at Maximum Load (0.968) and Modulus of Elasticity for Compression strength parallel to grain (0.751). All the remaining correlation values were found to be non-significant with moisture content.

xii) Compression strength parallel to grain at Maximum Load

Compression strength parallel to grain at Maximum Load was found positive and significantly correlated to Modulus of Elasticity for Compression strength parallel to grain (0.755). All the remaining correlation values were found to be non-significant with moisture content.

xiii) Compression strength perpendicular to grain at Limit of Proportionality

Compression strength perpendicular to grain at Limit of Proportionality was found positive and significantly correlated to Compression strength perpendicular to grain at 2.5mm (0.929) and Modulus of Elasticity for Compression strength perpendicular to grain (0.903). All the remaining correlation values were found to be non-significant with moisture content.

xiv) Compression strength perpendicular to grain at 2.5mm

Compression strength perpendicular to grain at 2.5mm was found positive and significantly correlated to Modulus of Elasticity for Compression strength perpendicular to grain (0.908). All the remaining correlation values were found to be non-significant with moisture content.

4.5.4) Simple correlation coefficients between chemical and anatomical properties of *Artocarpus heterophyllus* wood

The data pertaining to the correlation coefficient values between chemical and anatomical properties of *Artocarpus heterophyllus* are shown in Table 58. Out of total 153 combinations of simple correlation coefficients obtained between chemical and anatomical parameters, one was found to be positive and significant at 5% level of significance, one was found to be negative and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1% .

The correlation coefficients for different parameters are presented below as follows:

i) Cold water solubility

Cold water solubility was found to be negatively correlated and significant with ray width (-0.680).

ii) Hot water solubility

Hot water solubility was observed to be negative and significantly correlated with ray frequency (-0.862). Rests of the values for correlation coefficient were found to be non-significant.

iii) Holocellulose

Holocellulose elucidated positive and significant correlation with hemicellulose content (0.673) and Modulus of Elasiticity for Compression strength perpendicular to grain (0.763). Rest of the values for correlation coefficient were found to be non-significant.

4.5.5) Simple correlation coefficients between chemical and mechanical properties of *Artocarpus heterophyllus* wood

The data pertaining to the correlation coefficient values between chemical and mechanical properties of *Artocarpus heterophyllus* are shown in Table 59. Out of total 136 combinations of simple correlation coefficients obtained between chemical and mechanical parameters, eleven were found to be positive and significant at 1% level of significance, nine were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 5%.

The correlation coefficients for different parameters are presented below as follows:

i) Cold water solubility

Cold water solubility was found to be positively correlated and significant with Horizontal stress at limit of proportionality (0.771) and Fibre stress at limit of proportionality(0.746).

Table 58. Simple correlation coefficients between chemical and anatomical properties of *Artocarpus heterophyllus* wood

	CWS	HWS	ALBZ	LGN	HCE	CLE	HCLE	NaOH	Ash	FL	FD	VD	VA	VL	VF	RW	RH	RF
CWS																		
HWS	.641																	
ALBZ	.087	.227																
LGN	-.034	-.204	.252															
HCE	.007	.434	.296	-.275														
CLE	.489	.664	.344	.004	.566													
HCLE	-.431	-.084	.041	-.328	**.673***	-.229												
NaOH	.508	.365	.263	-.055	-.162	.006	-.196											
Ash	-.137	.262	.216	-.207	.082	-.365	.425	.020										
FL	.082	.596	-.283	-.377	.164	.235	-.018	.351	.069									
FD	-.456	-.065	.357	-.133	-.224	-.308	.012	.336	.403	.284								
VD	-.565	-.323	-.399	-.369	-.113	-.459	.278	-.639	.374	-.003	.065							
VA	-.281	-.013	-.139	-.062	-.516	-.442	-.213	-.212	.631	.136	.459	.633						
VL	-.145	.097	.198	-.080	.143	.420	-.207	.095	-.313	.267	.446	-.410	-.186					
VF	-.091	-.003	.096	-.477	.036	-.373	.376	.103	.664	-.120	.414	.108	.289	.136				
RW	**-.680***	.021	.075	.132	.269	-.002	.319	-.481	.309	.305	.315	.524	.406	.028	-.219			
RH	.420	.504	.115	-.386	.465	.232	.341	-.025	.511	-.071	-.222	-.101	-.031	-.030	.665	-.283		
RF	-.333	**-.862****	-.429	.032	-.451	-.608	.012	-.027	-.457	-.391	-.052	.051	-.244	-.035	.015	-.388	-.435	

*. Correlation is significant at the 0.05 level (2-tailed).

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

- **FL** - Fibre length
- **FD** - Fibre diameter
- **VD** - Vessel diameter
- **VA** - Vessel area
- **VL** - Vessel length
- **VF** - Vessel frequency
- **RW** - Ray width
- **RH** - Ray height
- **RF** - Ray frequency
- **CWS** - Cold water solubility
- **HWS** - Hot water solubility

- **ALBZ** - Alcohol benzene extractives
- **LGN** - Klason lignin content
- **HCE** - Holocellulose content
- **CLE** - Cellulose content
- **HCLE** - Hemicellulose content
- **NaOH** - Sodium hydroxide solubility

ii) Hot water solubility

Hot water solubility was observed to be positive and significantly correlated with Horizontal stress at limit of proportionality (0.734) and Fibre stress at limit of proportionality (0.680). Rests of the values for correlation coefficient were found to be non-significant.

iii) Klason lignin

Klason lignin was observed to be negative and significantly correlated with Modulus of Elasticity for Compression strength parallel to grain (0.734)

iv) Holocellulose

Holocellulose elucidated positive and significant correlation with hemicellulose content (0.673). Rest of the values for correlation coefficient were found to be non-significant.

v) Modulus of Rupture

Modulus of Rupture was observed to be positive and significantly correlated with Horizontal stress at maximum load (0.996), Horizontal stress at limit of proportionality (0.911), Modulus of Elasticity for Bending (0.934), Tension at maximum load (0.697) and Fibre stress at limit of proportionality (0.920).

vi) Horizontal stress at maximum load

Horizontal stress at maximum load was observed to be positive and significantly correlated with Horizontal stress at limit of proportionality (0.896), Modulus of Elasticity for Bending (0.940), Tension at maximum load (0.704) and Fibre stress at limit of proportionality (0.902).

Table 59. Simple correlation coefficients between chemical and mechanical properties of *Artocarpus heterophyllus* wood

	CWS	HWS	ALBZ	LGN	HCE	CLE	HCLE	MOR	HSatML	HSatLP	FSatLP	MOEB	TSat ML	CSPLat LP	MOECS PL	CSPRat LP	MOEC SPR
CWS																	
HWS	.641																
ALBZ	.087	.227															
LGN	-.034	-.204	.252														
HCE	.007	.434	.296	-.275													
CLE	.489	.664	.344	.004	.566												
HCLE	-.431	-.084	.041	-.328	**.673***	-.229											
MOR	.611	.487	-.295	-.441	.242	.021	.266										
HSatML	.587	.440	-.281	-.423	.190	-.053	.272	**.996****									
HSatLP	**.771***	**.734***	-.102	-.245	.262	.304	.037	**.911****	**.896****								
FSatLP	**.746***	**.680***	-.182	-.292	.254	.306	.025	**.920****	**.902****	**.984****							
MOEB	.463	.409	-.340	-.596	.191	-.061	.281	**.934****	**.940****	**.835****	**.844****						
TSatML	.173	.176	.034	-.565	.432	-.172	.664	**.697***	**.704***	.450	.469	.606					
CSPLatLP	.168	.312	.387	-.371	.270	-.100	.408	.543	.583	.514	.507	.592	**.674***				
MOECSPL	-.067	.395	.134	**-.716***	.282	-.020	.350	.357	.371	.338	.337	.562	.433	**.751***			
CSPRatLP	.143	.041	-.180	-.048	.492	.007	.574	.648	.648	.537	.583	.575	.537	.423	.067		
MOECSPR	.071	.082	.031	.034	.422	.023	.478	.520	.533	.483	.544	.454	.487	.616	.216	**.903****	

*. Correlation is significant at the 0.05 level (2-tailed).

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

- **CWS** - Cold water solubility
- **HWS** - Hot water solubility
- **ALBZ** - Alcohol benzene extractives
- **LGN** - Klason lignin content
- **HCE** - Holocellulose content
- **CLE** - Cellulose content
- **HCLE** - Hemicellulose content
- **MOR** - Modulus of Rupture
- **HS at ML** - Horizontal Stress at Maximum Load
- **CSPR at ML -** Compression perpendicular to grain at Maximum Load
- **HS at LP** - Horizontal Stress at Limit of Proportionality
- **FS at LP** - Fibre Stress at Limit of Proportionality
- **MOEB** - Modulus of Elasticity Bending
- **TS at ML** - Tensile Strength at Maximum Load
- **CSPL at LP** - Compression parallel to grain at Limit of Proportionality
- **MOE CSLP** - Modulus of Elasticity Compression parallel to grain
- **MOE CSPR -** Modulus of Elasticity Compression perpendicular to grain
- **CSPR at LP -** Compression perpendicular to grain at Limit of Proportionality

vii) Horizontal stress at limit of proportionality

Horizontal stress at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Bending (0.835) and Fibre stress at limit of proportionality (0.984).

viii) Fibre stress at limit of proportionality

Fibre stress at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Bending (0.844).

ix) **Tension at maximum load**

Tension at maximum load was observed to be positive and significantly correlated with Compression strength parallel to grain at limit of proportionality (0.674).

x) Compression strength parallel to grain at limit of proportionality

Compression strength parallel to grain at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Compression strength parallel to grain (0.751).

xi) Compression strength perpendicular to grain at limit of proportionality

Compression strength perpendicular to grain at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Compression strength perpendicular to grain (0.903).

4.5.6) Simple correlation coefficients between anatomical and mechanical properties of *Artocarpus heterophyllus* wood

The data pertaining to the correlation coefficient values between physical and anatomical properties of *Artocarpus heterophyllus* are shown in Table 60. Out of total 120 combinations of simple correlation coefficients obtained between anatomical and mechanical parameters, eight were found to be positive and significant at 1% level of significance, three were found to be positive and significant at 5% level of significance whereas, three was reported as negatively correlated and significant at 5%.

The correlation coefficients for different parameters are presented below as follows:

vii) Fibre diameter

Fibre diameter was found to be negatively correlated and significant with Compression strength perpendicular to grain at limit of proportionality (-0.745).

viii) Vessel length

Vessel length was observed to be negative and significantly correlated with Compression strength perpendicular to grain at limit of proportionality (-0.716) and Modulus of Elasticity for Compression strength perpendicular to grain (-0.771). Rests of the values for correlation coefficient were found to be non-significant.

ix) Ray height

Ray height was observed to be positive and significantly correlated with Tensile strength at maximum load (0.810).

x) Modulus of Rupture

Modulus of Rupture was observed to be positive and significantly correlated with Horizontal stress at limit of proportionality (0.911), Modulus of Elasticity for Bending (0.934), Tension at maximum load (0.697) and Fibre stress at limit of proportionality (0.920).

xi) Horizontal stress at limit of proportionality

Horizontal stress at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Bending (0.835) and Fibre stress at limit of proportionality (0.984).

Table 60. Simple correlation coefficients between anatomical and mechanical properties of *Artocarpus heterophyllus* wood

	FL	FD	VD	VA	VL	RW	RH	MOR	HSatLP	FSatLP	MOEB	TSatML	CSPLatLP	MOECSPL	CSPRatLP	MOECSPR
FL																
FD	.284															
VD	-.003	.065														
VA	.136	.459	.633													
VL	.267	.446	-.410	-.186												
RW	.305	.315	.524	.406	.028											
RH	-.071	-.222	-.101	-.031	-.030	-.283										
MOR	.192	-.503	.044	-.099	-.592	-.378	.597									
HSatLP	.313	-.493	-.125	-.094	-.513	-.277	.506	**.911****								
FSatLP	.253	-.578	-.016	-.060	-.541	-.273	.528	**.920****	**.984****							
MOEB	.332	-.351	.218	-.029	-.603	-.258	.372	**.934****	**.835****	**.844****						
TSatML	-.167	-.155	.164	-.064	-.350	-.268	**.810****	**.697***	.450	.469	.606					
CSPLatLP	-.094	.056	.333	.254	-.585	.067	.436	.543	.514	.507	.592	**.674***				
MOECSPL	.443	.369	.512	.397	-.190	.329	.226	.357	.338	.337	.562	.433	**.751***			
CSPRatLP	-.237	**-.745***	.206	-.352	**-.716***	-.003	.313	.648	.537	.583	.575	.537	.423	.067		
MOECSPR	-.337	-.609	.384	-.047	**-.771***	.200	.321	.520	.483	.544	.454	.487	.616	.216	**.903****	

*. Correlation is significant at the 0.05 level (2-tailed).

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

- **FL** - Fibre length
- **FD** - Fibre diameter
- **VD** - Vessel diameter
- **VA** - Vessel area
- **VL** - Vessel length
- **RW** - Ray width
- **RH** - Ray height
- **CSPR at LP** - Compression perpendicular to grain at Limit of Proportionality
- **MOE CSPR -** Modulus of Elasticity Compression perpendicular
- **MOR** - Modulus of Rupture
- **HS at LP** - Horizontal Stress at Limit of Proportionality
- **FS at LP** - Fibre Stress at Limit of Proportionality
- **TS at ML** - Tensile Strength at Maximum Load
- **CSPL at LP** - Compression parallel to grain at Limit of Proportionality
- **MOE CSLP** - Modulus of Elasticity Compression parallel to grain

xii) Fibre stress at limit of proportionality

Fibre stress at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Bending (0.844).

xiii) Tension at maximum load

Tension at maximum load was observed to be positive and significantly correlated with Compression strength parallel to grain at limit of proportionality (0.674).

xiv) Compression strength parallel to grain at limit of proportionality

Compression strength parallel to grain at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Compression strength parallel to grain (0.751).

xv) Compression strength perpendicular to grain at limit of proportionality

Compression strength perpendicular to grain at limit of proportionality was observed to be positive and significantly correlated with Modulus of Elasticity for Compression strength perpendicular to grain (0.903).

4.6) REGRESSION STUDIES

4.6.1) Multiple regression analysis

Table 61 presents the estimated linear relationships between the physical {(Moisture Content (X_1), Green Specific Gravity (Y_1), Oven dry Specific Gravity(Y_1), Tangential Shrinkage(Y_1), Radial Shrinkage(Y_1) and Volumetric Shrinkage(Y_1)} and chemical characteristics {Cold water soluble extractives (X_2) , Hot water soluble extractives (X_3) , Alcohol Benzene soluble extractives (X_4), Klason lignin (X_5), cellulose (X_6) and hemicellulose (X_7)}. Table 63a shows the estimated linear relationships between the physical and anatomical characteristics {Fibre length (X_2), Vessel diameter (X_3), Vessel length (X_4), Ray width (X_5)}. Table 64a gives the estimated linear relationships between the physical and anatomical characteristics {Vessel (%) (X_2), Parenchyma (%) (X_3), Fibre (%) (X_4) and Ray (%) (X_5)}. The linear relationships between the physical and mechanical characteristics {Modulus of Rupture (X_2), Modulus of Elasticity bending (X_3), Compression parallel to grain Modulus of Elasticity (X_4) and Compression perpendicular to grain Modulus of Elasticity (X_5)} are given in table 65. The data are presented below are under subtitles of dependent variables.

4.6.1.1) Multiple regression analysis between physical and chemical parameters

4.6.1.1.1) Green Specific Gravity (GSG)

R^2 value for Green Specific Gravity (GSG) when regressed with chemical characters was found 0.454 which indicates that 45.4 per cent of variability in GSG was due to parameters under study. Cellulose content (- 0.003) was negatively related, whereas rest of the parameters were positively related.

4.6.1.1.2) Oven dry Specific Gravity (OSG)

$R^2$was observed to be 0.932 for Oven dry Specific Gravity (OSG) which reveals that 93.2 per cent of variability in OSG was due to parameters under study. Cold water solubility (-0.020), cellulose content (-0.003) and hemicellulose content (-0.003) were negatively correlated whereas rest of the parameters were positively related.

4.6.1.1.3) Tangential shrinkage (TS)

R^2 value for Tangential shrinkage (TS) when regressed with chemical characters was found 0.918 which indicates that 91.8 per cent of variability in SB was due to parameters under study. Hot water solubility (-0.094) and alcohol benzene soluble extractives (0.001) were negatively related whereas rest of the parameters were positively related.

4.6.1.1.4) Radial shrinkage (RS)

R^2 value for Radial shrinkage (RS) when regressed with chemical parameters was found 0.940 which represents that 94 per cent of variability in RS was due to parameters under study. Except alcohol benzene soluble extractives (-0.124) other parameters were positively correlated.

4.6.1.1.5) Volumetric shrinkage (VS)

Coefficient of determination was observed to be 0.577 for Volumetric shrinkage (VS) and chemical parameters, which indicates that 57.7 per cent of variability in VS was due to parameters under study. Cold water extractives (-0.068) and alcohol benzene extractives (-0.149) were negatively correlated

4.6.1.2) Multiple regression analysis between physical and anatomical parameters

4.6.1.2.1) Green Specific Gravity (GSG)

R^2 value for Green Specific Gravity (GSG) when regressed with anatomical characters was found 0.848 which indicates that 84.8 per cent of variability in GSG was due to parameters under study. Vessel diameter (-0.001) and vessel length (-0.004) were negatively related, whereas rest of the parameters were positively related.

4.6.1.2.2) Oven dry Specific Gravity (OSG)

$R^2$was observed to be 0.679 for Oven dry Specific Gravity (OSG) and anatomical parameters, which reveals that 67.9 per cent of variability in OSG was due to parameters under study. Fibre length (-3.436E-005) was negatively related, whereas rest of the parameters were positively related.

4.6.1.2.3) Tangential shrinkage (TS)

R^2 value for Tangential shrinkage (TS) when regressed with anatomical characters was found 0.924 which indicates that 92.4 per cent of variability in TS was due to parameters under study. Fibre length (-0.011), vessel diameter (-0.176) and vessel length (-0.168) were negatively related.

Table 61. Multiple regression analysis between physical and chemical parameters

Parameters	Green Specific Gravity (Y_1)	Oven dry Specific Gravity (Y_2)	Tangential Shrinkage (Y_3)	Radial Shrinkage (Y_4)	Volumetric Shrinkage (Y_5)
Intercept	0.810	0.695	-7.665	-4.640	-3.780
Moisture Content (X_1)	-0.012	-0.002	-0.205	-0.122	0.005
CWS (X_2)	0.013	-0.020	0.529	0.135	-0.068
HWS (X_3)	0.001	0.016	-0.094	0.045	0.090
ALBZ (X_4)	0.005	0.002	-0.195	-0.124	-0.149
LGN (X_5)	0.003	0.002	0.345	0.184	0.094
CLE(X_6)	-0.003	-0.003	0.082	0.023	0.040
HCLE(X_7)	0.006	-0.003	0.322	0.252	0.183
R^2	0.454	0.932	0.918	0.940	0.577

*significant at 5 per cent level of significance

Table 62. Regression equations for physical and chemical parameters

$Y_1 = 0.810 - 0.012\ X_1 + 0.013\ X_2 + 0.001\ X_3 + 0.005\ X_4 + 0.003\ X_5 - 0.003\ X_6 + 0.006\ X_7$
$Y_2 = 0.695 - 0.002\ X_1 - 0.020\ X_2 + 0.016\ X_3 + 0.002\ X_4 + 0.002\ X_5 - 0.003\ X_6 - 0.003\ X_7$
$Y_3 = -7.665 - 0.205\ X_1 + 0.529\ X_2 - 0.094\ X_3 - 0.195\ X_4 + 0.345\ X_5 + 0.082\ X_6 + 0.322\ X_7$
$Y_4 = -4.640 - 0.122\ X_1 + 0.135\ X_2 + 0.045\ X_3 - 0.124\ X_4 + 0.184\ X_5 + 0.023\ X_6 + 0.252\ X_7$
$Y_5 = -3.780 + 0.005\ X_1 - 0.068\ X_2 + 0.090\ X_3 - 0.149\ X_4 + 0.094\ X_5 + 0.040\ X_6 + 0.183\ X_7$

- **CWS** - Cold water solubility
- **HWS** - Hot water solubility
- **ALBZ** - Alcohol benzene extractives
- **HCLE** - Hemicellulose content
- **CLE** - Cellulose content
- **LGN** - Klason lignin content

Table 63a. Multiple regression analysis between physical and anatomical parameters

Parameters	Green Specific Gravity (Y_1)	Oven dry Specific Gravity (Y_2)	Tangential Shrinkage (Y_3)	Radial Shrinkage (Y_4)	Volumetric Shrinkage (Y_5)
Intercept	2.269	0.544	99.876	50.284	29.105
Moisture Content (X_1)	-0.011	-0.001	-0.389	-0.209	-0.076
Fibre Length (X_2)	0.000	-3.436E-005	-0.011	-0.006	-0.002
Vessel Diameter (X_3)	-0.001	0.000	-0.176	-0.082	-0.022
Vessel Length (X_4)	-0.004	2.147E-005	-0.168	-0.093	-0.083
Ray Width (X_5)	0.004	0.003	0.213	0.144	0.110
R^2	0.848	0.679	0.924	0.753	0.807

*significant at 5 per cent level of significance

Table 63b. Regression equations for physical and anatomical parameters

Y_1= 2.269- 0.011 X_1+ 0.000 X_2- 0.001 X_3- 0.004 X_4+0.004 X_5- 0.005 X_6
Y_2= 0.554- 0.001 X_1- 3.436E-005 X_2+ 0.000 X_3+ 2.147E-005 X_4+ 0.003 X_5
Y_3= 99.876- 0.389 X_1- 0.011 X_2- 0.176 X_3- 0.168 X_4+0.213 X_5
Y_4= 50.284- 0.209 X_1- 0.006 X_2- 0.082 X_3- 0.093 X_4+ 0.144 X_5
Y_5= 29.105- 0.076 X_1- 0.002 X_2- 0.022 X_3- 0.083 X_4+ 0.110 X_5

Table 64a. Multiple regression analysis between physical and anatomical parameters

Parameters	Green Specific Gravity (Y_1)	Oven dry Specific Gravity (Y_2)	Tangential Shrinkage (Y_3)	Radial Shrinkage (Y_4)	Volumetric Shrinkage (Y_5)
Intercept	0.371	0.237	68.764	32.006	-3.234
Moisture Content (X_1)	-0.010	-0.002	-0.094	-0.035	0.001
Vessel (%) (X_2)	-0.009	-0.002	-0.763	0.005	0.067
Parenchyma (%) (X_3)	0.013	0.003	-0.170	-0.036	0.265
Fibre (%) (X_4)	0.007	0.005	-0.703	-0.347	0.047
Ray (%) (X_5)	-0.026	0.003	-1.625	-0.862	-0.487
R^2	0.811	0.176	0.899	0.686	0.613

*significant at 5 per cent level of significance

Table 64b. Regression equations for physical and anatomical parameters

$Y_1 = 0.371 - 0.010 X_1 - 0.009 X_2 + 0.013 X_3 + 0.007 X_4 - 0.026 X_5$
$Y_2 = 0.237 - 0.002 X_1 - 0.002 X_2 + 0.003 X_3 + 0.005 X_4 + 0.003 X_5$
$Y_3 = 68.764 - 0.094 X_1 - 0.763 X_2 - 0.170 X_3 - 0.703 X_4 - 1.625 X_5$
$Y_4 = 32.006 - 0.035 X_1 + 0.005 X_2 - 0.036 X_3 - 0.347 X_4 - 0.862 X_5$
$Y_5 = -3.234 + 0.001 X_1 + 0.067 X_2 + 0.265 X_3 + 0.047 X_4 - 0.487 X_5$

4.6.1.2.4) Radial shrinkage (RS)

R^2 value for Radial shrinkage (RS) when regressed with anatomical parameters was found 0.753 which represents that 75.3 per cent of variability in RS was due to parameters under study. Fibre length (-0.006), vessel diameter (-0.082) and vessel length (-0.093) were negatively correlated.

4.6.1.2.5) Volumetric shrinkage (VS)

R^2 was observed to be 0.807 for Volumetric shrinkage (VS) and anatomical parameters, which indicates that 80.7 per cent of variability in VS was due to parameters under study. Fibre length (-0.002), vessel diameter (-0.022) and vessel length (-0.083) were negatively correlated.

4.6.1.3) Multiple regression analysis between physical and tissue proportion parameters

4.6.1.3.1) Green Specific Gravity (GSG)

R^2 value for Green Specific Gravity (GSG) when regressed with cellular characters was found 0.81 which indicates that 81 per cent of variability in GSG was due to parameters under study. Vessel percent (- 0.009) and ray percent (-0.026) were negatively related.

4.6.1.3.2) Oven dry Specific Gravity (OSG)

R^2 was observed to be 0.18 for Oven dry Specific Gravity (OSG) and cellular parameters, which reveals that only 17 per cent of variability in OSG was due to parameters under study. Except Vessel percent (-0.002), all other parameters were positively correlated.

4.6.1.3.3) Tangential shrinkage (TS)

R^2 value for Tangential shrinkage (TS) when regressed with cellular characters was found 0.89 which indicates that 89 per cent of variability in TS was due to parameters under study. Vessel percent (-0.763), parenchyma percent (-0.170), fibre percent (-0.703) and ray percent (1.625) were negatively related.

Table 65. Multiple regression analysis between physical and mechanical parameters

Parameters	Green Specific Gravity (Y_1)	Oven dry Specific Gravity (Y_2)	Tangential Shrinkage (Y_3)	Radial Shrinkage (Y_4)	Volumetric Shrinkage (Y_5)
Intercept	0.650	0.589	7.603	3.977	1.254
Moisture content (X_1)	-0.009	-0.001	-0.139	-0.096	-0.049
MOR (X_2)	-8.440E-007	-1.450E-006	-1.808E-005	-9.336E-006	4.900E-005
MOEB (X_3)	1.545E-006	2.012E-006	0.000	-3.303E-005	-9.940E-006
MOECSPL (X_4)	1.111E-005	1.173E-006	0.000	0.000	0.000
MOECSPR (X_5)	8.819E-006	1.298E-005	0.001	0.000	-0.004
R^2	0.951	0.538	0.887	0.707	0.857

*significant at 5 per cent level of significance

Table 66. Regression equations for physical and mechanical parameters

$\mathbf{Y_1}$= -0.650- 0.009 $\mathbf{X_1}$-8.440E-007 $\mathbf{X_2}$+ 1.545E-006$\mathbf{X_3}$+1.111E-005 $\mathbf{X_4}$+ 8.819E-006 $\mathbf{X_5}$
$\mathbf{Y_2}$= 0.589-0.001$\mathbf{X_1}$-1.450E-006 $\mathbf{X_2}$+ 2.012E-006$\mathbf{X_3}$+ 1.173E-006 $\mathbf{X_4}$+ 1.298E-005 $\mathbf{X_5}$
$\mathbf{Y_3}$= 7.603-0.139 $\mathbf{X_1}$-1.808E-005 $\mathbf{X_2}$+ 0.000 $\mathbf{X_3}$ + 0.000 $\mathbf{X_4}$+ 0.001 $\mathbf{X_5}$
$\mathbf{Y_4}$= 3.977-0.096 $\mathbf{X_1}$-9.336E-006 $\mathbf{X_2}$-3.303E-005 $\mathbf{X_3}$ +0.000 $\mathbf{X_4}$+ 0.000 $\mathbf{X_5}$
$\mathbf{Y_5}$= 1.254-0.049 $\mathbf{X_1}$+ 4.900E-005 $\mathbf{X_2}$-9.940E-006 $\mathbf{X_3}$ +0.000 $\mathbf{X_4}$-0.004 $\mathbf{X_5}$

MOR - Modulus of Rupture
MOEB - Modulus of Elasticity Bending
MOE CSLP - Modulus of Elasticity Compression parallel to grain
MOE CSPR - Modulus of Elasticity Compression perpendicular to grain

4.6.1.3.4) Radial shrinkage (RS)

R^2 value for Radial shrinkage (RS) when regressed with cellular parameters was found 0.68 which represents that 68 per cent of variability in RS was due to parameters under study. Except Vessel percent (0.005), all other parameters were negatively correlated.

4.6.1.3.5) Volumetric shrinkage (VS)

$R^2$was observed to be 0.61 for Volumetric shrinkage (VS) and cellular parameters, which indicates that 61 per cent of variability in VS was due to parameters under study. Except ray percent (0.005), all other parameters were positively correlated.

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4.6.1.4) Multiple regression analysis between physical and mechanical parameters

4.6.1.4.1) Green Specific Gravity (GSG)

R^2 value for Green Specific Gravity (GSG) when regressed with mechanical characters was found 0.951which indicates that 95.1 per cent of variability in GSG was due to parameters under study. Rupture modulus (-8.440E-007) was negatively related.

4.6.1.4.2) Oven dry Specific Gravity (OSG)

R^2 was observed to be 0.538 for Oven dry Specific Gravity (OSG) and mechanical parameters, which reveals that 53.8 per cent of variability in OSG was due to parameters under study. Rupture modulus (-1.450E-006) was negatively related.

4.6.1.4.3) Tangential shrinkage (TS)

R^2 value for Tangential shrinkage (TS) when regressed with mechanical characters was found 0.887 which indicates that 88.7 per cent of variability in TS was due to parameters under study. Rupture modulus (-1.808E-005) was negatively related.

4.6.1.4.4) Radial shrinkage (RS)

R^2 value for Radial shrinkage (RS) when regressed with mechanical parameters was found 0.707 which represents that 70.7 per cent of variability in RS was due to parameters under study. Rupture modulus (-9.336E-006) and Bending Modulus of Elasticity (-3.303E-005) were negatively related.

4.6.1.4.5) Volumetric shrinkage (VS)

R^2 was observed to 0.857 for Volumetric shrinkage (VS) and mechanical parameters, which indicates that 85.7 per cent of variability in VS was due to parameters under study. Modulus of Elasticity Compression perpendicular to grain (-0.004) and Bending Modulus of Elasticity (-9.940E-006) were negatively related.

5. DISCUSSION

The results obtained from the study titled **"Wood property variation in jack trees (*Artocarpus heterophyllus* Lam.) grown in Thrissur district, Kerala"** are discussed in this chapter. In the current study, the Jackwood samples were collected from the local markets of three different zones in Thrissur based on three different girth classes *i.e.* 30 cm-60 cm, 60 cm-90 cm and 90 cm-120 cm. Three samples of each girth classes from different sites were collected which constitute 27 wood samples. The study focused on analysing these wood properties so as to understand their interrelationship which helps the wood to be utilized for desirable purposes.

5.1) PHYSICAL PROPERTIES OF WOOD

5.1.1) Colour and Texture

In case of Jackwood, even though the results obtained are similar, no significant variation had shown in case of colour and texture mainly due to the range of area we had selected for the study as the data recorded was confined to only Thrissur district of Kerala. The results of colour variation from the study of Haygreen and Bowyer (1982) studied different coniferous species from different locations observed colour variations which may be due to natural chemical extractives found in the wood. Through these deposits, the hues produced cover a wide range and are traceable to four spectral colours *viz*., red, orange, yellow and violet. Also, other natural influences, such as fungi, may also contribute to some colour variations. The wood colour parameters were relying on the chemical components that interact with light. The molecules having chromophore bindings in wood below and above the wavelength of 500 nm are lignin and phenolic extractives such as tannins, flavonoids, stilbenes and quinines respectively (Hon and Minemura, 2001). The wood colour could vary within a species due to the genetic factors (Rink and Phelps, 1989 and Mosedale *et al.*, 1996) and environmental conditions (Phelps *et al.*, 1982; Wilkins and Stamp, 1990). Hon and Minemura (2001) have shown that the interaction of chemical components with light is responsible for colour characteristics of wood and they have also recorded that lignin is the chromophore binding molecules in wood along with phenolic extractives such as tannin, flavonoids, quinines etc. This result can be compared to the studies carried out by Thulasidas *et al.* (2006) who noticed that no significant variation existed between teak samples collected from dry and moist area. On the other hand, our finding was contrary to information given by Knust (2009) that there was significant variation of L*, a* and b* value across the agro-ecological regions of Ghana. This variation can be attributed to geographical locations and soil characteristics of both the research sites. Insignificant variation in wood characteristics contributed to genetic factors, as wood colour within species varies with respect to genetic factors (Rink and Phelps, 1989; Mosedale *et al*., 1996). Tadashi *et al*. (2003) noticed that teak wood colour in wetter region was darker than drier area. Knust (2009) also stated that soil characteristics are related with wood colour of teak independent from effects of tree age as observed by Nelson *et al*. (1969) for walnut wood. The fact behind this was explained by Knust (2009) that accessibility of higher soil minerals to wood that eventually associate with its chomatophores in such a manner so as to absorb more light, thus reflecting lower light and thus the wood appearing darker.

5.1.2) Moisture content (%)

In the present study on Jack wood, no significant variation was observed for moisture content between the three altitudinal zones or between girth classes within these zones mainly because the confined range of area which we had taken so as to study the characteristics of species. The maximum moisture content observed was 41.79 %. Wood moisture generally vary within stems, commonly peaking towards the outer edges in the radial direction and declining toward the heartwood, leading to different moisture contents between heartwood and sapwood (Raczkowski *et al*., 2000; Spicer and Gartner, 2001). The moisture content variables have shown significant variations among core samples collected from different populations of *Dipterocarpus indicus* (Nageeb *et al*., 2010). The similar results have been reported by Sharma and Sharma (2005) in *Robinia pseudoacacia* and Raj *et al.* (2010) in Chir pine. The studies by Sunny *et al.,* (2019) on wood characteristics of *Dalbergia sissoo* procured from local markets found that highest moisture content of (20.17%) and maximum moisture content (68.33%) was recorded in the wood samples of Nalagarh site of Himachal Pradesh, India. Getahun *et al*. (2014) had observed variation in initial moisture content within tree in *Pinus patula* which showed decreasing trend from bottom to top of tree. Tsoumis (1991) observed that as the temperature and relative humidity of air varies, the equilibrium moisture content of the wood varies according to location. The hygroscopicity of wood depends upon the cellular composition of wood *i.e*., different types of cells, their cell wall thickness and lumen size. Suzuki (1999) observed that the moisture content may change with season and climate. He also noticed variations among populations for density, specific gravity as well as moisture content which may be influenced by the site factors.

5.1.3) Specific gravity

Wood species procured from different local market sites shows significant variation in specific gravity may be because of various components, including the geographic location of trees and moisture content which differs by species, d.b.h., age, and stem position (Miles and Smith, 2009). Purkayastha *et al.* (1980); Grzeskowiak *et al.* (2000) and Rao *et al.* (2002, 2003) have observed that the distinct species and sites have a significant impact on wood specific gravity. The difference in wood traits, *viz*., specific gravity, moisture content and tracheid length has been recorded at individual tree level, within individuals of a population and amongst sites or populations of a species.

In case of Jackwood, even though the values obtained are comparable no significant variation had shown in case of specific gravity mainly due to the range of area we had selected for the study as the data recorded was confined to only Thrissur district of Kerala. The maximum green specific gravity and oven dry specific gravity observed was 0.58 and 0.57 respectively. Morales (1987) have found highly significant differences in specific gravity between the 220 species from Mexican forests. By analyzing above table of sapwood and heartwood density, it has been observed that provenances with low elevations have more specific gravity as compared to higher elevation. The most probable reason for this is stressed conditions and variable site factors. Similar findings have been reported by Kennedy and Smith (1959) in *Populus trichocarpa*, as the location changed from good to poor, the specific gravity has shown increase from 0.331 to 0.383. Awang and Taylor (1993) have reported that values obtained for specific gravity at drier sites (0.6) were considerably higher than those at wetter sites (0.4) in *Acacia mangium.* Zobel and Buijtenen (1989) have also compared specific gravity in Sitka spruce of North and south provenances and observed that faster growing more southerly Sitka spruce provenances produced denser timber compared to slow growing more northerly provenances. Cox *et al.* (2001) have observed that specific gravity is heritable and the variations between wood are because of the genetic constitution and have found significant variations in the specific gravity of *Shorea acuminata, S. ovalis, S. leprosula* and *Dryobalanops aromatica.* Similarly, Martinez *et al.* (2009) have recorded that with precipitation and aridity than temperature, the wood density was more significantly correlated. As high wood density is achieved through reductions in cell size and increase in the proportion of wall compared to lumen and density is independent of vessel traits. Nageeb *et al*. (2010) have recorded significant variations in wood density of core samples procured from *Dipterocarpus indicus* of different populations. Igartual *et al.* (2003) have carried out studies on basic density at breast height of 35-year-old *Eucalyptus globulus* for character prediction of the whole tree and Wahlgren and Fassnacht (1959) have suggested that increment cores extracted at breast height could be safely used to estimate whole-tree density. Dhillon and Sidhu (2007) have measured specific gravity (at d.b.h) and noticed significant differences with respect to locations.

5.1.4) Shrinkage (%)

Wu *et al.*, (2012) observed that the eucalyptus wood impregnated with chemicals has significant decrease in shrinkage in volume as compared to untreated wood. Also, similar findings have been noticed by Gupta (2012) and Devi (2013). Bowyer *et al*., (2003); Pang (2002) and Walker (2006) have observed that in the transverse direction, shrinkage or swelling is more in the tangential than in the radial direction by a factor of 1.5-3. This is mainly due to the anatomical features of wood such as the presence of ray tissues, frequent pitting on radial walls, microfibril arrangements and earlywood-latewood interaction.

In the present study on Jackwood, significant variation was observed in volumetric, tangential and radial shrinkages between different zones which can be justified and compared to the results from rest of the studies. The coefficient (ratio of tangential and radial shrinkage or swelling) becomes smaller with increase in density (Kollmann and Cote, 1984). The negligible longitudinal wood swelling is accounted for the almost parallel orientation of the fibre in the longitudinal direction of wood. Boiciuc and Petrician (1970) also observed that removal of extractives greatly increased shrinkage and swelling of wood. Acoording to them, reduction in shrinkage and swelling was proportional to the space occupied by the extractives in the cell walls. Longitudinal wood swelling is very negligible. The higher swelling in tangential direction than in the radial direction is due to the greater amount of total wood substance in the tangential direction and also due to the fact that ray cells, which extend radially in the tree tend to restrain dimension changes (Stamm, 1964).

5.2) CHEMICAL PROPERTIES OF WOOD

5.2.1) Cold water-soluble extractives (%) and Hot water-soluble extractives (%)

The content, type and position of extracts affect the strength characteristics of wood (Narayanamurti and Verma, 1964) and the values for hot water-soluble extracts were higher than those of cold water. The difference insolubility was due to hydrolysis and corresponding increase in solubility of wood substance during the boiling with water. Similar results have been reported by Nazri *et al.* (2009) in *Leucaena* species. Maximum values for hot water extracts was due to the reason that hot-water extraction removes higher amount of materials, eliminates a portion of the cell structure and extracts some inorganic extracts (Shebani *et al.* 2008). Pari *et al.* (1997) have carried out studies on nine Indonesian species and they observed solubility in cold water, hot water and alcohol-benzene (1:2) which ranged from 4.33 to 7.41 per cent, 4.67 to 9.47 per cent and 1.99 to 9.21 per cent, respectively. The variation in solubility was due to hydrolysis and corresponding increase in solubility of wood substance during the boiling with water. In case of Jack wood based on the results obtained, we can clearly state that the values obtained are comparable with the studies mentioned above which had been given to support the data.

5.2.2) Alcohol benzene soluble extracts (%)

The data obtained by the chemical analysis of Jack wood can be justified by the studies and it had shown significant variation between girth classes within the zones. Alton *et al.* (1990) reported that heartwood contained significantly more extracts than sapwood. The variation in water soluble and chemical soluble extracts of toon wood are in conformity with the studies conducted by Shirsat (2011) in *Acacia nilotica,* Liang (2004) in *Acacia mangium,* Mahdavi *et al*. (2004) in *Eucalyptus camaldulensis,* Kumar *et al.* (2005) in *Dalbergia sissoo*, Silva *et al.* (2005) in *Eucalyptus grandi,* Morais *et al.* (2005) in *Pinus oocarpa*. Yang *et al.* (2009) have also reported significant differences between 1 per cent NaOH extraction contents of *Bambusa chungii*. Alcohol-benzene soluble extractive of wood was an important character representing extracts present in wood which affect the quality of pulp. The components which are generally soluble in alcohol-benzene are oleoresins, fats and waxes. The results of the present investigations are in conformity with the studies conducted by Liang and Joshi (2004) on Aspen tree, Mahdavi *et al*. (2004) on *Eucalyptus camaldulensis,* Hernandez and Salazar (2006) in *Quercus coccolobifolia, Q. rugosa* and *Q. oleoides* and Fakhrian *et al.* (2005) on *Alnus glulmosa*.

5.2.3) Klason lignin content (%), Holocellulose content (%), Cellulose (%), Hemicellulose (%), NaOH solubility (%) and Ash content (%)

The data obtained from the chemical analysis of Jack wood was in accordance with the previous studies conducted on various species but not much variation had been obtained for all the parameters except for NaOH solubility due to the confined range of area which we had selected for our present study. Adi *et al*. (2011) noticed that the lignin content in *Meranti* bunga was lower than that of *Meranti* bakau and *Meranti* sangkan and hence, any wood that has low lignin content and high α-cellulose content would be a good potential to be utilized as raw material for pulp and paper making and bioethanol production. Beleam and Harkin (1975) have observed that lignin content varies among species, individuals and within plant. Similar results have been reported by different researcher in *Leucaena leucocephala* (Diaz *et al.,* 2007 and Lopez *et al.,* 2008), which are in assurance with the results of the current work. Sczukowski *et al.* (2008) have observed difference in lignin and holocellulose contents of *Salix viminalis* and its cross with *Salix purpurea*. Kumar (2000) while working on *Dalbergia sissoo* and Beleam and Harkin (1975) in *Eucalyptus* hybrid have also reported the similar findings. Adi *et al.* (2011) while working on branchwood of *Meranti* have observed the similar trends in both lignin and holocellulose contents. Alton *et al.* (1990) have reported that sapwood contained more holocellulose than heartwood. Among different provenances, significant variations have been noticed where, holocellulose ranged from 67.05-73.82 per cent and lignin content ranged from 21.03-25.95 per cent. Cellulose and hemicellulose together described as holocellulose is used to denote the polysaccharides in wood. The holocellulose content is a quantitative indication of fibrous raw material influencing consideration of its suitability for pulp. Whereas, lignin is a phenolic substance which consist of an irregular array of variously bonded hydroxyl- and methoxy-substituted phenyl-propane units, which is distributed throughout the secondary cell wall with the highest concentration in middle lamella and is responsible for providing stiffness to the cell wall. Alen (2000) observed that it also serves to bond individual cells together in the middle lamella region and several common wood species have ash contents ranging from 0.43% (aspen) to 0.87% (white oak) (Mishra *et al.,* 2004).

5.3) ANATOMICAL PROPERTIES OF WOOD

5.3.1) Fibre morphology

Wani and Khan (2010) have observed significant variation in the wood anatomical features *viz.* fibre length, fibre wall thickness from different positions of trees of *Populus nigra* L. Sykes *et al.* (2006) have also reported that fibre length can be controlled genetically and is not under influence of environmental fluctuations. Nguyen *et al*. (2009) found that the wood fibre length of *Acacia mangium* and *Acacia auriculiformis* increased from the pith to periphery in the wood. Izekor and Fuwape (2011) observed *Tectona grandis* wood and stated that the fibre length of the wood was higher in older wood among the group of trees. Similar results have been obtained by Malan and Gerischer, (1987) while working on eucalyptus and they have observed that fibre length increased due to growth stress. Jiang *et al*. (2004) have also noticed significant variation in fibre length of *Leucaena leucocephala* and *Populus* varieties. Tavares *et al.* (2011) have observed significant site differences in *Acacia melanoxylon* for fibre length. Nisgoski *et al*. (2011) have revealed that the mean values of fibre length and fibre width, increased from pith to bark and fibre wall thickness had a little variation. Saravanan (2013) observed that the fibre length and fibre width had significant increment with increase in age and also from pith to periphery while working on *Melia dubia* wood.

In the present study on Jack wood even though the values obtained were comparable with the studies which had mentioned above for different species, no significant variation was observed in most of the parameters except for wall thickness. The reason could be mainly due to the confinement of area *i.e.* Thrissur district which had been selected to study the variation in wood characteristics. Significant results for fibre characteristics were found by Marcati *et al.* (2014) when comparing wood anatomy of root and stem of *Citharexylum myrianthum* in Brazil. Igartual *et al.* (2003) have carried out studies on fibre length at breast height of 35-year-old *Eucalyptus globulus* for parameter prediction of the whole tree. The fibre length at breast height reflects whole tree have been shown by Raymond and MacDonald (1998), Jorge *et al*. (2000), Chauhan *et al.* (2001) and Baha (2002). Kaeiser (1956) has reported that average fibre length increased successively with the number of rings from the pith to outwards. Kaubaa *et al.* (1998) have found similar results in the hybrids of poplars and same findings have also been observed by Chauhan *et al*. (1999) and Chauhan *et al.* (2001). Yang and Zuo (2003) reported the variation of fibre length and fibre width for seven poplar clones and they noticed that fibre length and width increased from pith to bark. The variability in anatomical characteristics has profound influence on characteristics of wood (Burley and Palmer, 1979). The general pattern of variation in wood element dimensions was observed not only within a species but has also been observed within a tree (Rao and Rao, 1978; Pande *et al.*, 1995). Fibre length is a vital property studied for determining the end use of wood. Ghouse and Siddiqui (1976) also gave the information that phloem fibre formed from combined effect of intrusive growth and fusiform cells resulted in aging of cambium. Fibre length was found to be highest in central mid land i.e. 1814.94 µm and lowest in coastal sandy i.e. 1054.13 µm (Table 15); this range was also found in *Artocarpus nitidus* (1193.73 µm) and *A. lakoocha* (1425 µm).

Anoop *et al*. (2014) observed that fibre length of *A. hirsutus* was more than *Artocarpus heterophyllus* i.e. 1803.45 µm which is comparable to our finding. Tavares *et al.* (2011) revealed that in *Eucalyptus globulus* wood, the fibre length decreased from the bottom to the top of the tree and increased from the pith to the bark. Izekor and Fuwape (2011) carried out *Tectona grandis* wood and reported that the mean values of fibre diameter were 26.79 µm, 29.47 µm and 32.83 µm. Wood anatomy especially the proportion and distribution of the microstructure is very crucial to wood identification and utilization. Structure and dimension of cell change within same species (Seralde, 2006). Similar results have been obtained by Malan and Gerischer (1987) while working on eucalyptus have observed that fibre length increased due to growth stress. Jiang *et al*. (2004) have also noticed significant variation in fibre length of *Leucaena leucocephala* and *Populus* varieties.

Tavares *et al.* (2011) have observed significant site differences in *Acacia melanoxylon* for fibre length. Nisgoski *et al*. (2011) have also revealed that the mean values of fibre length and fibre width, increased from pith to bark and fibre wall thickness had a little variation. Fibre length, fibre diameter and cell wall thickness increased with increase in age. Saravanan (2013), while working on *Melia dubia* wood has observed that the fibre length and fibre width had significant increment with increase in age and also from pith to periphery. Burley and Palmer (1979) noticed the variability in anatomical characteristics has great influence on characteristics of wood. The general pattern of variation in wood element dimensions was observed not only within a species but has also been observed within a tree (Rao and Rao, 1978; Pande *et al.,* 1995). Sunny *et al.* (2019) from his studies on *Dalbergia sissoo* wood recorded that maximum fibre diameter (20 µm) and fibre length (1660 µm) was observed in the wood samples from Dattowal and Ghumarwin site of Himachal Pradesh respectively. Verghese *et al*. (2000) noticed that there was no significant difference in fibre characters of 60 years old teak among nine different locations in Peninsular lndia. The fibre wall thickness for Aini ranged between 5.12 µm to 5.95 µm which can be comparable to the findings by Singh *et al*. (2017) who found fibre wall thickness of 4.90 µm in *Artocarpus nitidus*. Naji *et al*. (2011) revealed that fibre wall thickness in *Hevea brasiliensis* was 3.98 µm to 4.88 µm in Tok Dor from Rubber Research Institute Mini Station (RRIMINIS) in 4.88 µm in Malaysia.

Pulps having very good flexibility and Runkel ratios can yield pulps with acceptable breaking length, tear and burst indices suitable for newsprint paper production (Jimenez *et al.,* 1993; Scott *et al.,* 1995). A number of researchers suggested an approximate range of runkel ratio applicable to pulp and paper production, 0.25 to 1.5 by Singh *et al.* (1991); less than 1 by Dadswell and Wardrop (1959) and less than or equal to 1 by Okereke (1964) per and Rydholm (1965). Ratios, indices and factors derived from fibre dimensions are equally important as fibre morphology while considering raw material for pulp and paper industry. Snook et al. (1986) reported desirable values of runkel ratio, slenderness ratio and flexibility coefficients both in hardwoods and softwoods. According to him the values of runkel ratio, slenderness ratio and flexibility coefficients are 0 .35, 95-120 and 75 respectively for softwoods and 0.4-0.7, 55-70 and 55-75 respectively for hardwoods. Slenderness ratio is directly proportional to fibre length and inversely proportional to fibre cell wall thickness. Fibers having longer and thinner cell walls are producing a good slenderness ratio. Higher the slenderness ratio, greater will be the expected flexibility that will give better tensile and tear property. Slenderness ratio is also related with resistance to tearing (Rydholm. 1965). Dutt *et al.* (2004) reported that increase in slenderness ratio results in paper with low degree of collapsibility and conformability within the sheet. Lower the collapsibility value, easier it is to drain water from the wet end of the paper-machine (Foelkel, 1998). According to Ogbonnaya *et al.* (1997) fibres with poor slenderness ratio do not produce good surface contact and fiber-to-fiber bonding which reduces not its mechanical strength characteristics and fibres having high slenderness ratio suitable for writing, printing, wrapping and packaging purposes. It was observed that if the slenderness ratio of a fibrous material is lower than 70, it is not valuable for quality pulp and paper production (Young, 1981; Bektas *et al*, 1999).

5.3.2) Vessel morphology

Vessel diameter did not vary significantly between zones or girth classes. Singh *et al*. (2017) also found the same range for *Artocarpus nitidus i.e.* 277.92 µm. Vessel diameter is also related to water conductivity and water availability of the site. But from the safety point of view Zimmerman (1983) showed that short vessel elements were more resistant to collapse and deformation. In *Artocarpus hirsutus* Lam., smaller vessel length was observed (Table 11) which was also found in teak under particulate pollution stress (Anoop *et al*., 2017). Here the vessel length was short as per the classification given by Metcalfe and Chalk (1950) *i.e.* when the mean length of vessel member is less than 350um, it is described as short and when the mean length is over 800 µm, it is described as long.

Similar results of vessel length were also reported by Sahoo *et al.* (2017) for *Artocarpus hirsutus* Lam. wood grown in Thrissur district, Kerala. In 2006, Heinrich and Banks have found that *Toona ciliata* exhibited large latitudinal distributions, and thus it can be expected that their wood anatomies also vary because of shifts in the environmental conditions of the respective climate zones where, they grow in. Christensen *et al*. (2007) have reported that vessel dimensions differed within the trees, as smallest vessels and the lowest vessel frequency have been observed in the parts of the trees subjected to the greatest stresses or strains. Ramirez *et al.* (2009) have reported wide range of variation in *Eucalyptus globules* clones for vessel frequency, vessel area and vessel coverage among the clones. From pith to bark, mean vessel area and vessel coverage has increased gradually, whereas the vessel frequency has decreased. In 2011, Nisgoski *et al*. have observed that mean values of vessel element length, tangential diameter of vessel lumen in *Toona ciliata* increased from pith to bark but vessels per square millimeter decreased. Clara (2012) reported that vessel length and vessel diameter increases from closer spacing to wider spacing and vessel frequency decreases from closer spacing to wider spacing *Eucalyptus urophylla* and she also noticed significant difference in vessel frequency, resulting from an increased or decreased propensity of cambial initials to become this cell type, as well as vessel size, occurs in response to change in site conditions and moisture availability which have impact on the physiology of the trees (David *et al*., 2009). Several authors have pointed out that water availability is one of the most important environmental sources of variation of the vessel anatomy of different species such as *Eucalyptus spp., Fagus sylvatica, F. moesiaca* and *Quercus robur* (Carlquist, 1975 and Leal *et al.*, 2003). Vessel frequency in *Artocarpus hirsutus* was found to be 2-3/mm^2 across all the zones. Most of the vessels were found to be solitary. This may be due to the higher frequency of vessels; smaller the diameter, and greater the chance for grouping of vessels (Vijayan *et al.*, 2017) and the same frequency has been observed in teak by Cardoso *et al*. (2015) from East Timor. The analysis revealed that no significant differences existed between zones or girth classes as all the three zones were experiencing more or less similar rainfall pattern and also since vessel frequency is mostly related to water conductivity.

A low value for vulnerability (1.0) and mesomorphy (75) indicated adaptation to xeric condition *i.e* it can withstand the low water availability while high value of vulnerability and mesomorphy indicate the adaptation of species to mesic. According to Meena *et al.* (2014) who carried out studies on parameters in *Albizia procera* and observed that vulnerability of *A. procera* in in tropical condition was 85.10 in Bangladesh and Mesomorphy in tropical area varied from to 10970 to 31999.10. These findings are similar to our study and *Artocarpus heterophyllus* proved efficient enough in conductivity due to its large vessel area and few numbers. According to Carlquist (1977) the vessel parameters is controlled by length or fusiform initials. Vessel diameter and vessel area were found higher in midland. This can be explained by the finding that long and wide vessels are adaptable to mesic condition where soil moisture and relative humidity is high. Poorter (2008) observed that wider vessels lead to higher flow rate due to increased cross-sectional area of lumen and Anfodilo *et al.* (2006) also showed that conduit dimensions were influenced by environnmental factors like water deficit.

When the above-mentioned studies were compared with the data recorded from the analysis of Jack wood, we could observe similar results were obtained. Except for the fact that apart from vessel length, all other parameters showed no significant variation between the zones or girth classes within the zones.

5.3.3) Ray morphology and Tissue proportion

Sahu and Gopakumar (2005) have noticed that the ray height, width and ray frequency vary in *Albizzia odoratissima* and *Samania saman.* Meena and Gupta (2014) have also observed variable ray height ranging from 171.45-344.76 µm in *Albizia procera* and reported significant variations in most microscopic features between localities. Nisgoski *et al*. (2011) have noticed that ray width increased and rays per millimeter (ray frequency) decreased from pith to bark in *Toona ciliata.* Rahman *et al.* (2005) have reported highest ray volume in teak wood samples showing higher specific gravity. Kollman and Cote (1984) explained that shrinkage differs in three different directions due to the influence of wood rays and different arrangements of fibrils on cell walls.

With reference to the similar studies, in case of Jack wood, we could observe comparable results with respect to each of the parameter that had been taken into account for the study. Carlquist (2001) noted that along with moisture availability and freezing effect on xylem anatomy, geographical location of a wood sample also affects structure, or phenology, e.g., slope exposure, rainfall, deciduous nature of plant, leaf size, or seasonal stem dieback. Therefore, it can be inferred that the above difference can be attributed to slope and exposure as all the three zones have different topographical features. Nevertheless, environmental factors clearly do affect some aspects of xylem structure, as shown for soil fertility and wood density (Muller-Landau, 2004), soil water and vessel diameter (Stevenson and Mauseth, 2004), climate and growth rings (Wang *et al.*, 2005), and vessel diameter (Thomas *et al.*, 2007). Radial parenchymatous rays facilitate flow in radial direction in trees and helps in identification as their width and height range widely. Parenchymatous rays of toon wood are mostly seen as moderate broad and multi-serrate (3-5) with different frequency in longitudinal tangential sections. Variations have been noticed in its dimensions (length and width) and also in frequency among different toon provenances. The parameters are affected by both genetic and environmental factors. Rahman *et al.* (2005) have reported highest ray volume in teak wood samples showing higher specific gravity. Kollman and Cote (1968) explained that shrinkage differs in three different directions due to the influence of wood rays and different arrangements of fibrils on cell walls.

5.4) MECHANICAL PROPERTIES OF WOOD

5.4.1) Static bending test

Kamala *et al.* (2014) have observed that mature wood of *Pinus patula* yields more grades with high values of MOR. Macchioni (2001) in Atlas cedar (*Cedrus atlantica*); Rao *et al.* (1972) and Sunny *et al.* (2019) on *Dalbergia sissoo*; Purkayastha and Kazmi (1985) in case of *Tectona grandis* have also similar results. Sharmin *et al.* (2015) observed that the mixed plantation wood of S*wietenia macrophylla* grown in Chittagong region showed MOE 104051.84 kg/cm^2 and MOR 622 kg/cm^2 which were relatively lower than the wood of *Tectona grandis*. Rao *et al.* (1972) in *Dalbergia sissoo* wood and Purkayastha and Kazmi (1985) in *Tectona grandis* wood also reported the similar results. Ali (2011) also found significant variations in rupture modulus of ntholo (*Pseudolachnostylis maprounaefolia* Pax), metil (*Sterculia appendiculata* K. Schum) during his doctoral research on the physical-mechanical characteristics and natural durability of lesser used wood species from Mozambique.

The studies on Jack wood showed comparable data with respect to the studies mentioned except for the fact that there was not significant variation found for the characteristics considered for the study mainly due to the limited range of area that had considered for carrying out the work. Chauhan *et al*. (2002) in his studies on White *Meranti* and Sal and also by Rao *et al*. (1972) in *Dalbergia sissoo* had found similar results. The bending strength of wood varies with the presence of knots, cellular compositions, cell wall depositions, extractives and even the growth characteristics. Olufemi and Malami (2011) have also noticed that *Eucalyptus camaldulensis* have an average density of 977.58 kg/m^3, static bending strength of 1356 kg/cm^2 and the elastic modulus of 155199.68 kg/cm^2. Awan *et al.* (2012) carried out studies on the mechanical characteristics of farm-grown *Eucalyptus camaldulensis* Dehn. in comparison to conventional timbers *i.e.*, *Dalbergia sissoo* Roxb., *Acacia nilotica* Del. and *Cedrus deodara* Roxb. and have observed variable values for different species and have reported *Cedrus deodara* is a good commercial timber with excellent bending strength (661 kg/cm^2). Saravanan (2014) has revealed in his study on *Meila dubia* that age have a significant effect on static bending i.e., static bending improves with age. Ali (2011) has also noticed significant variations in bending strength of ntholo (*Pseudolachnostylis maprounaefolia* Pax), metil (*Sterculia appendiculata* K. Schum) during his research on the physico-mechanical characteristics and natural durability of lesser used wood species from Mozambique.

Variation in the values of bending elastic modulus for different species and locations can be attributed to the growth conditions, locality, edaphic factors as well as the difference in chemical characteristics of cell wall. Similar results have been observed by Bier (1984) while studying *Pinus radiata* and Kumar (2016) in *Pinus roxburghii.* Izekor and Fuwape (2011) carried out studies on *Tectona grandis* wood in Edo State, Nigeria and stated that the mean values of bending elastic modulus were 77792.72 (kg/cm^2), 69284.01 (kg/cm^2), 62380.83 (kg/cm^2); 109361.30 (kg/cm^2), 100405.75 (kg/cm^2), 93686.43 (kg/cm^2); 140162.85 (kg/cm^2), 130386.01 (kg/cm^2), 122436.71 (kg/cm^2) for 15, 20 and 25 years old *Tectona grandis* wood respectively. Similarly, Carrillo *et al.* (2011) analysed the wood from fourteen native species from Northeast Mexico were studied with regard to their elastic modulus (MOE), basic density and rupture modulus (MOR) and relationship between these three characteristics. The results revealed that the MOE range was 65465.78 kg/cm^2 to 154283.06 kg/cm^2 corresponding to *Diospyros texana* and *Acacia schaffneri*, respectively.

5.4.2) Tensile Strength at Maximum Load (kg/cm^2)

Sanwo (1986) observed that the rate of growth has no significant influence on specific gravity and strength characteristics of plantation-grown teak in Nigeria. Verma *et al.* (2012) analysed the tensile characteristics of bamboo laminae prepared from slivers, selected from different regions of bamboo culms (*Dendrocalamus strictus*) and noticed that these characteristics increased from inner to outer region for any cross section and from bottom to top. Awan *et al.* (2012) observed the tensile strength in *Eucalyptus camaldulensis* and other mechanical characteristics and have also noticed similar type of variations. The variations in strength characteristics of a species is mainly attributed to its genetic characteristics, however variation in wood structure due to growth and presence of defects also affects the strength characteristics. Vergas *et al.* (2012) have also observed in *Salix* species that intrinsic characteristics and site may influence the tensile strength. Kumar (2016) has also noticed similar results for *Pinus roxburghii* and similar results have been observed for tensile strength in *Ostrya carpinifolia* wood by Korkut and Guller (2007).

When compared to the results recorded for Jack wood, the data analysed from the similar studies for other species were similar and could be taken into account for relating and interpreting the various characteristics that were studied except the fact that characteristics for Jackwood revealed no significant variation between the zones or for girth classes within the zones. When external forces act on a piece of timber in a direction away from its end or such that the fibres are pulled apart, the timber is said to be subjected to tensile stresses which gives the ability of timber to resist these stretching forces is referred to its tensile strength. Wood is being used as a constructional material since ages and is certainly subjected to different forces while in use. Statistically significant variation has been observed in tensile strength among different species from different sites which can be attributed to various factors including environmental, genetic, as well as the size of cells, chemical composition (contribution of structural compounds), degree of polymerisation and crystallisation of cellulose. Brunetti *et al.* (2001) in Atlas cedar (*Cedrus atlantica* Manetti); Korkut and Guller (2007) in *Ostrya carpinifolia* and Kumar (2016) in *Pinus roxburghii* wood have reported similar results. Sanwo (1986) has reported that the variation in strength characteristics of a species is mainly attributed to its genetic characteristics. Siddiqui and Mahmood (1986); Sturion *et al.* (1987); Brouard *et al.* (1989) and Siddiqui *et al.* (1989) have also shown similar results. However, variation in wood structure due to growth and presence of defects also affects the strength characteristics in wood.

5.4.3) Compression strength

Rahman *et al.* (2005) have observed that teak trees having highest ray volume indicated higher specific gravity and greater compression strength irrespective of the fact that ray proportion remains the same across pith to bark. Izekor and Modogu (2010) carried out studies on the effects of density on variations in the mechanical characteristics of plantation grown *Tectona grandis* wood aged 15, 20 and 25-year and found that mean density values on oven dry weight and volume basis have 480, 556 and 650 Kg m^{-3}, rupture modulus as 783.75 kg/cm^2, 1059.99 kg/cm^2 and 1373.45 N kg/cm^2, elastic modulus as 69819.15 kg/cm^2, 101161.35 kg/cm^2 and 130988.36 kg/cm^2, compressive strength parallel to grain as 446.02 kg/cm^2, 596.23 kg/cm^2 and 768.45 kg/cm^2 for 15, 20 and 25-year old *Tectona grandis* wood. Variation in compression parallel to grain in different wood species can be assigned to factors *viz*., wood porosity and cellular composition. The presence of extractives and lignin depositions also influence the compressive strength of wood and in general the wood is strongest in parallel to grain because cells are aligned in this direction and have strong linkage. The cellular orientation perpendicular to the grain makes the wood weaker in compression as cell layers in this direction may have variable cell types with weaker linkages. Awan *et al.* (2012) recorded the mechanical characteristics of farm-grown *Eucalyptus camaldulensis* Dehn. in comparison to conventional timbers *i.e., Dalbergia sissoo* Roxb., *Acacia nilotica* Del. and *Cedrus deodara* Roxb. Izekor *et al*. (2010) observed the effects of density on variations in the mechanical characteristics of the wood from *Tectona grandis* plantation and have registered significant variations in strength characteristics. If wood is considered a bundle of straws bound together, then a compression parallel to grain can be thought of a force trying to compress the straws from end to end (Rowell, 2013). The cellular orientation perpendicular to the grain makes the wood weaker in compression as cell layers in this direction may have variable cell types. Saravanan *et al.* (2014) carried out studies on mechanical characteristics using different age gradation *viz.*, three, four and five years of *Melia dubia* wood samples and found variation in each year growth. Among the age gradations five-year-old *M. dubia* registered maximum value for elastic modulus compression parallel to grain and confirmed the suitability of five-year-old wood as raw material for plywood, pencil and light furniture industry.

Aydin and Yardimci (2007) carried out studies for compression strength perpendicular to grain for poplar, fir, pine and hornbeam and have observed that compression parallel to grain is higher than compression perpendicular to grain. The cellular orientation perpendicular to the grain makes the wood weaker in compression as cell layers in this direction may have variable cell types. Rahman *et al.* (2005) have noticed similar results for Teak wood samples for mechanical characteristics. They observed that highest ray volume shows higher specific gravity and greater compression strength irrespective of the fact that ray proportion remains the same across pith to bark. Izekor *et al.* (2010) reported the effects of density on variations in the mechanical characteristics of plantation grown *Tectona grandis* wood aged 15, 20 and 25-years. Luo *et al.* (1997) carried out studies on wood density and mechanical characteristics of 32 clones of Chinese firs (*Cunnighamia lanceolata*) and have revealed variation in mechanical characteristics of these clones. Zahabu *et al.* (2015) have evaluated the effects of spacing on growth, yield, and wood characteristics of teak and observed similar findings. Leclercq (1997) has observed that the white willow has a higher impact bending strength, elasticity and sensibly higher rigidity as compared to Euramerican poplar clones. Kiaei (2011) observed the variations of the mechanical characteristics of Elm wood along longitudinal direction and the studies reported that stem height had significant effect on elastic modulus and decreased along longitudinal direction from the base to top. In the present work, there is a significant variation among the samples of wood collected from different sites. The results obtained for Jack wood could be compared and found similar to the above-mentioned works done on similar species except for the fact that apart from Elastic modulus Compression Perpendicular to the grain all other characteristics showed no significant difference between the zones.

5.5) SIMPLE CORRELATION COEFFICIENTS

Correlation coefficient is a statistical tool which assists to measure and analyze the degree of relationship between two variables. Beery *et al*. (1983) have observed differences between the tangential and radial compression strength among hardwood species and have revealed that the between-species differences of lateral compression strength occur because of the ray volume. Shepard and Shottafer (1992) reported a significant linear relationship between wood density and mechanical characteristics of timber. Zhang (1995) have shown that rupture modulus and the maximum crushing strength in compression parallel to the grain are most closely and almost linearly related to wood specific gravity, whereas, elastic modulus was poorly and least linearly related to specific gravity. Specific gravity is usually considered as a good indicator of the wood strength because the greater the amount of substance, the higher the specific gravity and therefore higher the strength (Olsson *et al*., 1947). Wang *et al.* (1996) studied the correlation between growth characteristic and wood quality characteristics of 7 years old poplar (*Populus*) and observed relatively high positive correlation between plant height and DBH, fibre length and length width ratio and wood specific gravity and DBH. Dinwoodie (2000) has stated that density is the best predictor of timber strength. The analysis done based on the correlation between different wood characteristics of Jack revealed comparable results with respect to the studies which were mentioned above and could be used for further studies on Jack wood in the future.

5.6) REGRESSION STUDIES

'Regression analysis' is a method by which estimates are made for the value of variables from the knowledge of the values of one or more other variables and to the measurement of errors involved in estimation process. In the present study, the coefficient of determination has been noticed to be high in all the characteristics of mechanical strength when regressed with physico-chemical characteristics of wood except in bending strength where, it is revealed to be moderate.

Montes *et al.* (2007) have observed coefficient of determination for compression parallel to grain which is approximately 30 per cent of the variation in longitudinal direction (R^2 = 0.322; $p < 0.001$). Stronger relationships in these characteristics have however been reported for other hardwood species also at older ages (Bucur, 1983; Hernandez *et al.,* 1998; Oliveira *et al.,* 2002). Kiae and Samariha (2011) had conducted the studies on fibre dimensions, physical and mechanical characteristics of five important hardwood plants and the obtained results which showed a positive correlation between wood density and MOR (R^2=0.709), elastic modulus (R^2=0.792), and compression parallel to the grain (R^2=0.693) at species levels. Okoh (2014) carried out studies on the physical and mechanical characteristics of Ghanaian hardwoods and noticed that there were positive correlations between wood density and compression parallel to grain (R^2=0.644), rupture modulus (R^2= 0.680) and Elastic modulus (R^2= 0.646) at four different species level. The results of study revealed a significant linear relationship between wood density and mechanical strength characteristics of timber.

Zhang (1995), Shepard and Shottafer (1992) have noticed a significant linear relationship between density and mechanical characteristics of wood. According to Dinwoodie (1996), the rupture modulus and the maximum crushing strength in compression parallel to the grain are most closely and almost linearly related to wood density whereas, elastic modulus is poorly and least linearly related to wood density. Ling *et al.* (2015) have given regression equation for basic density, rupture modulus, compression parallel to grain, hardness of transverse section, hardness of radial section and hardness of tangential section for major tree species in China. They observed that all coefficients of regression equations (R^2) have been higher than 0.75. When the regression analysis was done between the wood characteristics of Jack wood in combination with one another, the results obtained found to be comparable when similar studies on other species were taken into account.

SUMMARY

The present investigation entitled **"Wood property variation in jack trees (*Artocarpus heterophyllus* Lam.) grown in Thrissur district, Kerala"** had been carried out in the Department of Forest Products and Utilization, College of Forestry, Kerala Agricultural University, Thrissur, Kerala. The present work was carried out with the following objectives:

- To study the variation in physical properties of Jackwood.
- To study the variation in chemical properties of Jackwood.
- To study the variation in anatomical properties of Jackwood.
- To study the variation in mechanical properties of Jackwood.
- Correlation and regression studies

The results for the present investigations are summarized as under:

- The values of L* ranged from 59.78 to 61.32 for lowland, 56.69 to 58.61 for midland and 57.98 to 61.44 for highland. The analysis on the current data showed no significant variation between the zones and also girth within the zones. The values of a* ranged from 9.83 to 10.68 for lowland, 10.49 to 11.75 for midland and 9.69 to 11.81 for highland. There was no significant variation observed between the zones and girth within zones. The values of b* ranged from 38.23 to 41.62 for lowland, 38.80 to 40.02 for midland and 37.07 to 40.42 for highland There was no significant variation observed between the zones and girth within zones. All the wood samples from the different girth classes within different zones had the medium texture wood. The moisture content values ranged from 40.15% to 44.55% for lowland, 35.65% to 41.63% for midland and 37.22% to 41.71% for highland. There was no significant variation observed between the zones and girth within zones.

- The green specific gravity values ranged from 0.47 to 0.57 for lowland, 0.56 to 0.60 for midland and 0.53 to 0.54 for highland. Analysis of data revealed that there was no significant variation present across three zones as well as between girth classes within zones of Thrissur district of Kerala. The values of oven dry specific gravity ranged from 0.54 to 0.57 for lowland, 0.55 to 0.58 for midland and 0.54 to 0.57 for highland. The data shows no significant variation across three zones as well as between girth classes within zones of Thrissur district of Kerala.

- The values of volumetric shrinkage ranged from 3.63% to 4.26% for lowland, 4.78% to 5.38% for midland and 3.47% to 3.91% for highland. Analysis of the data revealed significant variation between zones and not between girth classes within zone. The tangential shrinkage values ranged from 3.16% to 3.90% for lowland, 4.73% to 6.45% for midland and 3.31% to 4.31% for highland. The radial shrinkage values ranged from 1.98% to 2.45% for lowland, 2.96% to 3.95% for midland and 2.07% to 2.18% for highland. For both tangential and radial shrinkage, significant variation was observed for the zones and no variation for girth classes within the zones.

- The values of cold-water solubility ranged from 1.81% to 2.19% for lowland, 2.19% to 2.50% for midland and 2.31% to 4.55% for highland. A critical observation of the data revealed no significant variations among zones and girth classes within the zones. The values of hot water solubility ranged from 3.75% to 6.47% for lowland, 6.05% to 6.77% for midland and 6.94% to 7.28% for highland. There was no significant variation observed between the zones and girth within zones. Alcohol-benzene solubility values ranged from 10.69% to 15.91% for lowland, 11.58% to 12.54% for midland and 10.49% to 13.47% for highland. There was no significant variation between zones but significant variation was found for the girth classes within zones. The values of klason lignin ranged from 26.32% to 30.65% for lowland, 24.27% to 30.77% for midland and 23.47% to 29.11% for highland. There was no significant variation observed between the zones and girth within zones.

- Holocellulose values ranged from 66.19% to 70.55% for lowland, 65.46% to 76.13% for midland and 69.41% to 70.24% for highland. There was no significant variation observed between the zones and between girth within zones. The cellulose values ranged from 39.95% to 43.24% for lowland, 39.24% to 44.46% for midland and 42.76% to 46.02% for highland. In case of the percentage of cellulose content which is analysed from different showed no significant variation between the zones and girth classes within zones. Hemicellulose values of ranged from 26.82% to 27.90% for lowland, 26.22% to 32.95% for midland and 23.45% to 27.49% for highland. As cellulose, the hemicellulose content showed no variation difference between zones. The values of NaOH solubility ranged from 17.34% to 23.76% for lowland, 15.32% to 19.79% for midland and 19.92% to 22.70% for highland. There was significant variation observed between the zones but not for girth within zones. The ash content values ranged from 0.52% to 0.76% for lowland, 0.66% to 0.94% for midland and 0.50% to 0.89% for highland. There was no significant variation observed between the zones and between girth classes within zones.

- The fibre length values ranged from 1040.43 µm to 1083.13 µm for lowland, 1047.27 µm to 1089.40 µm for midland and 1063.84 µm to 1139.06 µm for highland. There was no significant variation observed between the zones and between girth classes within zones. The values for fibre diameter ranged from 21.45 µm to 23.22 µm for lowland, 20.45 µm to 21.69 µm for midland and 20.10 µm to 22.15 µm for highland. There was no significant variation observed between the zones and between girth classes within zones. The lumen width values ranged from 13.76 µm to 15.66 µm for lowland, 11.58 µm to 15.17 µm for midland and 12.55 µm to 14.67 µm for highland. There was no significant variation observed between the zones and between girth classes within zones. Wall thickness values ranged from 3.78 µm to 3.88 µm for lowland, 3.26 µm to 4.43 µm for midland and 3.77 µm to 4.43 µm for highland. There was no significant variation observed between the zones whereas variation was observed for girth classes within zones.

- The runkel ratio values ranged from 0.49 to 0.56 for lowland, 0.43 to 0.78 for midland and 0.58 to 0.67 for highland. There was no significant variation observed between the zones and for girth classes within zones. The slenderness ratio values ranged from 93.80 to 96.98 for lowland, 98.88 to 104.06 for midland and 97.30 to 105.83 for highland. There was no significant variation observed between the zones and for girth classes within zones. Shape factor values ranged from 0.38 to 0.42 for lowland, 0.34 to 0.52 for midland and 0.39 to 0.47 for highland. The FL-FD ratio values ranged from 46.90 to 48.49 for lowland, 49.44 to 52.03 for midland and 48.65

to 52.92 for highland. There was no significant variation observed between the zones and for girth classes within zones for both shape factor and FL-FD ratio.

- The values of vessel diameter ranged from 204.19 µm to 220.78 µm for lowland, 217.42 µm to 221.13 µm for midland and 203.79 µm to 216.43 µm for highland. There was no significant variation observed between the zones and for girth classes within zones. The vessel area values ranged from 25477.35 $µm^2$ to 27480.33 $µm^2$ for lowland, 25025.74 $µm^2$ to 29291.47 $µm^2$ for midland and 24630.26 $µm^2$ to 27512.11 $µm^2$ for highland. There was no significant variation observed between the zones and for girth classes within zones. The values of vessel length ranged from 237.41 µm to 244.31 µm for lowland, 226.57 µm to 241.03 µm for midland and 234.88 µm to 245.36 µm for highland. There was no significant variation observed between the zones but variation was observed for girth classes within zones. The vessel frequency values ranged from 5.00 no. / mm^2 for lowland, 4.93 no. / mm^2 to 5.00 no. / mm^2 for midland and 4.73 no. / mm^2 to 5.44 no. / mm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The values of vulnerability index ranged from 42.99 to 44.53 for lowland, 43.23 to 46.26 for midland and 38.77 to 45.40 for highland. There was no significant variation observed between the zones and for girth classes within zones. For vessel mesomorphy, the values ranged from 10200.84 to 10630.56 for lowland, 10057.95 to 10476.90 for midland and 9402.18 to 11145.42 for highland. There was no significant variation observed between the zones and for girth classes within zones.

- The ray width values ranged from 38.44 µm to 45.17 µm for lowland, 44.73 µm to 45.24 µm for midland and 36.13 µm to 45.96 µm for highland. There was no significant variation observed between the zones but variation was observed for girth classes within zones. The values of ray height ranged from 408.83 µm to 424.60 µm for lowland, 427.33 µm to 444.83 µm for midland and 412.84 µm to 472.81 µm for highland. There was no significant variation observed between the zones and for girth classes within zones. The vessel per cent values ranged from 1.88% to 2.33% for lowland, 2.31% to 2.81% for midland and 1.94% to 2.92% for highland. There was no significant variation observed between the zones and girth classes within zones. The parenchyma per cent values ranged from 32.27% to 35.67% for lowland, 31.48% to

40.15% for midland and 32.32% to 39.11% for highland. There was no significant variation observed between the zones and for girth classes within zones. The fibre per cent values ranged from 51.28% to 58.53% for lowland, 49.55% to 58.68% for midland and 49.75% to 55.86% for highland. There was no significant variation observed between the zones and for girth classes within zones. The ray per cent values ranged from 8.56% to 10.71% for lowland, 7.47% to 10.05% for midland and 8.22% to 10.85% for highland. There was no significant variation observed between the zones but variation was observed for girth classes within zones.

- The MOR values ranged from 467.62 kg/cm^2 to 574.09 kg/cm^2 for lowland, 572.87 kg/cm^2 to 923.79 kg/cm^2 for midland and 599.40 kg/cm^2 to 832.26 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The Maximum load values ranged from 105.35 kg to 116.12 kg for lowland, 119.03 kg to 176.59 kg for midland and 114.22 kg to 158.90 kg for highland. There was no significant variation observed between the zones and for girth classes within zones. For HS at ML, the values ranged from 17.89 kg/cm^2 to 21.72 kg/cm^2 for lowland, 20.45 kg/cm^2 to 33.03 kg/cm^2 for midland and 21.40 kg/cm^2 to 29.74 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The HS at LP values ranged from 14.75 kg/cm^2 to 15.74 kg/cm^2 for lowland, 16.29 kg/cm^2 to 19.50 kg/cm^2 for midland and 17.00 kg/cm^2 to 20.10 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones.

- FS at LP values ranged from 412.55 kg/cm^2 to 440.87 kg/cm^2 for lowland, 462.81 kg/cm^2 to 545.32 kg/cm^2 for midland and 476.24 kg/cm^2 to 562.19 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The values of MOEB ranged from 48262.93 kg/cm^2 to 57423.41 kg/cm^2 for lowland, 48165.96 kg/cm^2 to 80653.92 kg/cm^2 for midland and 62277.93 kg/cm^2 to 69379.70 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The values of TS at ML ranged from 607.20 kg/cm^2 to 677.63 kg/cm^2 for lowland, 665.74 kg/cm^2 to 873.46 kg/cm^2 for midland and 537.86 kg/cm^2 to 883.85 kg/cm^2 for highland. The present study indicates non-significant results for tensile strength of wood samples collected from different sites. The CSPL at LP values ranged from 245.22 kg/cm^2 to 366.67 kg/cm^2 for lowland, 250.15 kg/cm^2 to 388.45 kg/cm^2 for midland and 243.90 kg/cm^2 to 342.08 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones.

- The values of CSPL at ML ranged from 379.93 kg/cm^2 to 459.72 kg/cm^2 for lowland, 350.95 kg/cm^2 to 514.75 kg/cm^2 for midland and 367.35 kg/cm^2 to 443.38 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The MOE CSPL values ranged from 26005.11 kg/cm^2 to 37772.21 kg/cm^2 for lowland, 24628.42 kg/cm^2 to 39421.74 kg/cm^2 for midland and 28561.36 kg/cm^2 to 35662.67 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The CSPR at LP values ranged from 92.86 kg/cm^2 to 111.49 kg/cm^2 for lowland, 119.04 kg/cm^2 to 149.23 kg/cm^2 for midland and 92.90 kg/cm^2 to 121.86 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The values of CSPR at 2.5mm ranged from 128.97 kg/cm^2 to 191.76 kg/cm^2 for lowland, 218.08 kg/cm^2 to 251.31 kg/cm^2 for midland and 165.59 kg/cm^2 to 210.82 kg/cm^2 for highland. There was no significant variation observed between the zones and for girth classes within zones. The data for MOE CSPR ranged from 17996.12 kg/cm^2 to 22340.02 kg/cm^2 for lowland, 23221.65 kg/cm^2 to 26012.12 kg/cm^2 for midland and 17410.08 kg/cm^2 to 22074.66 kg/cm^2 for highland. There was no significant variation observed between the zones but variation was observed for girth classes within zones.

- Out of total 153 combinations of simple correlation coefficients obtained between physical and chemical characteristics, four were found to be positive and significant at 1% level of significance, two were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1% and one was reported as negatively correlated and significant at 5% level of significance. Highly significant and positive correlation was noticed for a*value with ash content; volumetric shrinkage with green specific gravity; tangential shrinkage with radial shrinkage; holocellulose content with hemicellulose content.

The negative and significant correlation has been recorded for L*value with a*value; green specific gravity with NaOH soluble extractives content.

- Out of total 153 combinations of simple correlation coefficients obtained between physical and anatomical characteristics, three were found to be positive and significant at 1% level of significance, three were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1% and one was reported as negatively correlated and significant at 5% level of significance. Highly significant and positive correlation was noticed for volumetric shrinkage with tangential shrinkage and radial shrinkage; tangential shrinkage with radial shrinkage; oven dry specific gravity with vessel area and ray width. The negative and significant correlation has been recorded for L*value with a*value, tangential shrinkage with fibre diameter.

- Out of total 210 combinations of simple correlation coefficients obtained between physical and mechanical characteristics, twenty were found to be positive and significant at 1% level of significance, ten were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1%. Highly significant and positive correlation was noticed for volumetric shrinkage with green specific gravity, Compression strength perpendicular to grain at Limit of Proportionality, Compression strength perpendicular to grain at 2.5mm and Modulus of Elasiticity for Compression strength perpendicular to grain, tangential shrinkage and radial shrinkage; tangential shrinkage with radial shrinkage; green specific gravity with Compression strength perpendicular to grain at 2.5mm and Modulus of Elasiticity for Compression strength perpendicular to grain; rupture modulus with Horizontal stress at Maximum Load, Horizontal stress at Limit of Proportionality, Fibre Stress at Limit of Proportionality, Elastic modulus Bending and Tensile Strength at Maximum Load; Horizontal stress at Maximum Load with Horizontal stress at Limit of Proportionality, Fibre Stress at Limit of Proportionality, Elastic modulus Bending, Tensile Strength at Maximum Load and Compression strength parallel to grain at Maximum Load; Fibre Stress at Limit of Proportionality with Elastic modulus Bending; Elastic modulus Bending with Compression strength parallel to grain at Maximum Load; Tensile Strength at

Maximum Load with Compression strength parallel to grain at Maximum Load and Compression strength parallel to grain at Limit of Proportionality; Compression strength parallel to grain at Limit of Proportionality with Compression strength parallel to grain at Maximum Load and Elastic modulus for Compression strength parallel to grain; Compression strength parallel to grain at Maximum Load with Elastic modulus for Compression strength parallel to grain; Compression strength perpendicular to grain at Limit of Proportionality with Compression strength perpendicular to grain at 2.5mm and Elastic modulus for Compression strength perpendicular to grain; Compression strength perpendicular to grain at 2.5mm with Elastic modulus for Compression strength perpendicular to grain. The negative and significant correlation has been recorded for L*value with a*value, tangential shrinkage with fibre diameter.

- Out of total 153 combinations of simple correlation coefficients obtained between chemical and anatomical characteristics, one was found to be positive and significant at 5% level of significance; one was found to be negative and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1%. Highly significant and positive correlation was noticed for Holocellulose with hemicellulose content. The negative and significant correlation has been recorded for Cold water solubility with ray width and Hot water solubility with ray frequency.

- Out of total 136 combinations of simple correlation coefficients obtained between chemical and mechanical characteristics, eleven were found to be positive and significant at 1% level of significance, nine were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 5%. Highly significant and positive correlation was noticed for Cold water solubility with Horizontal stress at limit of proportionality; Hot water solubility with Horizontal stress at limit of proportionality and Fibre stress at limit of proportionality; Holocellulose with hemicellulose content; Rupture modulus with Horizontal stress at maximum load, Horizontal stress at limit of proportionality, Elastic modulus for Bending, Tension at maximum load and Fibre stress at limit of proportionality; Horizontal stress at maximum load with Horizontal stress at limit of proportionality , Elastic modulus for Bending, Tension at maximum load and Fibre stress at limit of proportionality; Horizontal stress at limit of proportionality with Elastic modulus for Bending and Fibre stress at limit of proportionality; Fibre stress at limit of proportionality with Elastic modulus for Bending; Tension at maximum load with Compression strength parallel to grain at limit of proportionality; Compression strength parallel to grain at limit of proportionality with Elastic modulus for Compression strength parallel to grain; Compression strength perpendicular to grain at limit of proportionality with Elastic modulus for Compression strength perpendicular to grain.

- Out of total 120 combinations of simple correlation coefficients obtained between anatomical and mechanical characteristics, eight were found to be positive and significant at 1% level of significance, three were found to be positive and significant at 5% level of significance whereas, three was reported as negatively correlated and significant at 5%. Highly significant and positive correlation was noticed for Ray height with Tensile strength at maximum load; Rupture modulus with Horizontal stress at limit of proportionality, Elastic modulus for Bending, Tension at maximum load and Fibre stress at limit of proportionality; Horizontal stress at limit of proportionality with Elastic modulus for Bending and Fibre stress at limit of proportionality; Fibre stress at limit of proportionality with Elastic modulus for Bending; Tension at maximum load with Compression strength parallel to grain at limit of proportionality; Compression strength parallel to grain at limit of proportionality with Elastic modulus for Compression strength parallel to grain; Compression strength perpendicular to grain at limit of proportionality with Elastic modulus for Compression strength perpendicular to grain. The negative and significant correlation has been recorded for Fibre diameter with Compression strength perpendicular to grain at limit of proportionality; Vessel length with Compression strength perpendicular to grain at limit of proportionality and Elastic modulus for Compression strength perpendicular to grain.

- Coefficient of determination (R^2) was observed to be 0.454 for green specific gravity (Y_1), 0.932 for oven dry specific gravity (Y_2), 0.918 for tangential shrinkage (Y_3), 0.940 for radial shrinkage (Y_4) and 0.577 for volumetric shrinkage (Y_5) when regressed with physical and chemical characteristics.

- Coefficient of determination (R^2) was observed to be 0.848 for green specific gravity (Y_1), 0.679 for oven dry specific gravity (Y_2), 0.924 for tangential shrinkage (Y_3), 0.753 for radial shrinkage (Y_4) and 0.807 for volumetric shrinkage (Y_5) when regressed with physical and anatomical characteristics.

- Coefficient of determination (R^2) was observed to be 0.811 for green specific gravity (Y_1), 0.176 for oven dry specific gravity (Y_2), 0.899 for tangential shrinkage (Y_3), 0.686 for radial shrinkage (Y_4) and 0.613 for volumetric shrinkage (Y_5) when regressed with physical and anatomical characteristics.

- Coefficient of determination (R^2) was observed to be 0.951 for green specific gravity (Y_1), 0.538 for oven dry specific gravity (Y_2), 0.887 for tangential shrinkage (Y_3), 0.707 for radial shrinkage (Y_4) and 0.857 for volumetric shrinkage (Y_5) when regressed with physical and mechanical characteristics.

Analysis revealed that except for volumetric, tangential and radial shrinkage, all other physical properties didn't show any significant variation across three altitudinal zones as well as between girth classes. Alcohol benzene soluble extractives and NaOH soluble extractives showed significant difference between girth classes within zone and between altitudinal zones respectively when chemical properties were taken into account. When it comes to anatomica properties, wall thickness, vessel length, ray width and ray (%), rest of the characteristics didn't show significant difference. No significant differences were observed for the mechanical characteristics except for MOECSPR. From the study and analysis of the all these characteristics, we can state that the wood procured from 'midland' can be put for better utilization taking into account high a* value, specific gravity and all the mechanical properties except for HS at LP, FS at LP and MOEB are higher than rest of the zones. Comprehensive study and baseline data on physical, chemical, anatomical and mechanical wood properties of jack wood was done for the first time that can be used for future tree improvement programmes which helps the industries to put jack wood for more unexplored end uses.

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WOOD PROPERTY VARIATION IN JACK TREES (*Artocarpus heterophyllus* Lam.) GROWN IN THRISSUR DISTRICT, KERALA

By

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ABSTRACT

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ABSTRACT

The present research entitled “Wood property variation in jack trees (*Artocarpus heterophyllus* Lam.) grown in Thrissur district, Kerala" was carried out in the Department of Forest Products and Utilization, College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur, during 2017-2020. The species belonging to the family Moraceae and popularly known as jackfruit tree, is one of the important timber species commonly found in the homegardens of Kerala. The objective of this study was to assess the variation in physical, chemical, anatomical and mechanical properties of Jack wood (*Artocarpus heterophyllus* Lam.) between different altitudinal zones (Lowland, Midland and Highland) and girth classes within these altitudinal zones of Thrissur district, Kerala.

Samples of Jack wood were collected from the three altitudinal zones (Lowland, Midland and Highland) of Thrissur district belonging to three girth classes viz., 30 cm - 60 cm, 60 cm - 90 cm. and 90 cm -120 cm, following stratified random sampling techniques. In the case of physical properties such as color, moisture content, green specific gravity, oven dry specific gravity, volumetric shrinkage, tangential shrinkage and radial shrinkage, analysis showed variation between the zones for the all the three types of shrinkages. Chemical analysis of the wood for water soluble and chemically soluble extractives showed significant variation in the case of alcohol benzene soluble extractives and for NaOH soluble extractives. Rest of the parameters such as cold-water soluble extractives, hot water-soluble extractives, holocellulose content, klason lignin content, cellulose content, hemicellulose content and ash content showed no significant variation. Jack wood is diffuse porous with aliform parenchyma surrounding solitary vessels, sometimes forming bands and broad to finely arranged rays. The anatomical parameters when analyzed, showed significant variation for ray morphological characteristics whereas vessel morphology, fibre morphology and ecoanatomical properties showed no significant variation. The mechanical parameters studied which includes static bending, tension, compression and its sub parameters showed no significant variation except for Modulus of Elasticity compression perpendicular to grain.

Simple correlation coefficients obtained between physical and chemical parameters, four were found to be positive and significant at 1% level of significance, two were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1% and one was reported as negatively correlated and significant at 5% level of significance. The simple correlation coefficients obtained between physical and anatomical parameters, three were found to be positive and significant at 1% level of significance, two were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1% and one was reported as negatively correlated and significant at 5% level of significance. Simple correlation coefficients obtained between physical and mechanical parameters, twenty were found to be positive and significant at 1% level of significance, ten were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1%. The simple correlation coefficients obtained between chemical and anatomical parameters, one was found to be positive and significant at 5% level of significance, one was found to be negative and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 1%. Simple correlation coefficients obtained between chemical and mechanical parameters, eleven were found to be positive and significant at 1% level of significance, nine were found to be positive and significant at 5% level of significance whereas, one was reported as negatively correlated and significant at 5%. The simple correlation coefficients obtained between anatomical and mechanical parameters, eight were found to be positive and significant at 1% level of significance, three were found to be positive and significant at 5% level of significance whereas, three was reported as negatively correlated and significant at 5%. Coefficient of determination (R^2) was observed to be more than 0.70 for oven dry specific gravity, tangential shrinkage and radial shrinkage when regressed with physical and chemical parameters. When regressed between physical and anatomical parameters R^2 was observed to be more than 0.70 for green specific gravity, tangential shrinkage, radial shrinkage and volumetric shrinkage. Coefficient of determination (R^2) was observed to be more than 0.70 for green specific gravity, tangential shrinkage, radial shrinkage and volumetric shrinkage when regressed with physical and mechanical parameters.

APPENDIX-I

1. Analysis of variance for L* value of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	28.943	14.472	2.98 ^{ns}
GIRTH(ZONE)	6	29.055	4.843	0.29 ^{ns}
Error	18	305.458	16.970	
Total	27	363.456		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

2. Analysis of variance for a* value of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	4.167	2.084	1.21 ^{ns}
GIRTH(ZONE)	6	10.250	1.708	1.66 ^{ns}
Error	18	18.460	1.026	
Total	27	32.877		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

3. Analysis of variance for b* value of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	6.994	3.497	0.57 ^{ns}
GIRTH(ZONE)	6	36.927	6.154	0.56 ^{ns}
Error	18	199.765	11.098	
Total	27	243.686		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

4. Analysis of variance for moisture content (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.371	0.186	1.72 ^{ns}
GIRTH(ZONE)	6	0.647	0.108	0.15 ^{ns}
Error	18	13.163	0.731	
Total	27	14.181		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

5. Analysis of variance for green specific gravity of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.020	0.010	3.33 ^{ns}
GIRTH(ZONE)	6	0.017	0.003	0.83 ^{ns}
Error	18	0.062	0.003	
Total	27	0.100		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

6. Analysis of variance for oven dry specific gravity of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.001	0.000	0.00 ^{ns}
GIRTH(ZONE)	6	0.005	0.001	1.94 ^{ns}
Error	18	0.007	0.000	
Total	27	0.013		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

7. Analysis of variance for volumetric shrinkage (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.475	0.238	13.22*
GIRTH(ZONE)	6	0.111	0.018	0.29 ^{ns}
Error	18	1.133	0.063	
Total	27	1.719		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

8. Analysis of variance for tangential shrinkage (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	1.049	0.525	7.00*
GIRTH(ZONE)	6	0.451	0.075	0.58 ^{ns}
Error	18	2.341	0.130	
Total	27	3.841		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

9. Analysis of variance for radial shrinkage (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.842	0.421	16.19*
GIRTH(ZONE)	6	0.158	0.026	0.38 ^{ns}
Error	18	1.261	0.070	
Total	27	2.261		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

10. Analysis of variance for cold water solubility (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.818	0.409	4.44 ^{ns}
GIRTH(ZONE)	6	0.555	0.092	0.82 ^{ns}
Error	18	2.025	0.113	
Total	27	3.398		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

11. Analysis of variance for hot water solubility (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.684	0.342	3.22 ^{ns}
GIRTH(ZONE)	6	0.633	0.106	1.56 ^{ns}
Error	18	1.222	0.068	
Total	27	2.540		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

12. Analysis of variance for alcohol benzene soluble extractives (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.300	0.150	0.70 ^{ns}
GIRTH(ZONE)	6	1.277	0.213	5.08*
Error	18	0.754	0.042	
Total	27	2.331		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

13. Analysis of variance for klason lignin (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.275	0.137	0.61^{ns}
GIRTH(ZONE)	6	1.354	0.226	1.93^{ns}
Error	18	2.108	0.117	
Total	27	3.736		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

14. Analysis of variance for holocellulose (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.097	0.049	0.38^{ns}
GIRTH(ZONE)	6	0.767	0.128	2.53^{ns}
Error	18	0.907	0.050	
Total	27	1.772		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

15. Analysis of variance for cellulose (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.155	0.077	0.54^{ns}
GIRTH(ZONE)	6	0.860	0.143	0.61^{ns}
Error	18	3.049	0.169	
Total	27	4.065		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

16. Analysis of variance for hemicellulose (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.040	0.020	0.07^{ns}
GIRTH(ZONE)	6	1.756	0.293	0.61^{ns}
Error	18	8.587	0.477	
Total	27	10.383		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

17. Analysis of variance for NaOH solubility (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	3.126	1.563	5.69*
GIRTH(ZONE)	6	1.644	0.274	1.68 ^{ns}
Error	18	2.935	0.163	
Total	27	7.705		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

18. Analysis of variance for ash content (%) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.039	0.019	0.68 ^{ns}
GIRTH(ZONE)	6	0.167	0.028	1.66 ^{ns}
Error	18	0.302	0.017	
Total	27	0.508		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

19. Analysis of variance for fibre diameter (µm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	7.636	3.818	1.49 ^{ns}
GIRTH(ZONE)	6	15.308	2.551	1.59 ^{ns}
Error	18	28.860	1.603	
Total	27	51.805		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

20. Analysis of variance for fibre length (µm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	6848.780	3424.390	1.28 ^{ns}
GIRTH(ZONE)	6	16006.903	2667.817	0.68 ^{ns}
Error	18	70112.573	3895.143	
Total	27	92968.257		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

21. Analysis of variance for lumen width (µm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	14.187	7.094	0.96 ns
GIRTH(ZONE)	6	44.073	7.346	2.22 ns
Error	18	59.618	3.312	
Total	27	117.878		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

22. Analysis of variance for wall thickness (µm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	1.373	0.686	1.34 ns
GIRTH(ZONE)	6	3.053	0.509	3.19*
Error	18	2.865	0.159	
Total	27	7.290		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

23. Analysis of variance for runkel ratio of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.103	0.051	1.37 ns
GIRTH(ZONE)	6	0.220	0.037	2.43 ns
Error	18	0.272	0.015	
Total	27	0.595		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

24. Analysis of variance for slenderness ratio of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	294.841	147.421	5.04 ns
GIRTH(ZONE)	6	175.503	29.250	0.84 ns
Error	18	627.636	34.869	
Total	27	1097.980		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

25. Analysis of variance for shape factor of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.017	0.009	0.75^{ns}
GIRTH(ZONE)	6	0.070	0.012	1.45^{ns}
Error	18	0.145	0.008	
Total	27	0.232		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

26. Analysis of variance for FL-FD ratio of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	73.703	36.851	5.04^{ns}
GIRTH(ZONE)	6	43.872	7.312	0.84^{ns}
Error	18	156.908	8.717	
Total	27	274.483		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

27. Analysis of variance for vessel diameter (µm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	87.900	43.950	0.25^{ns}
GIRTH(ZONE)	6	1037.940	172.990	1.45^{ns}
Error	18	2146.852	119.270	
Total	27	3272.692		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

28. Analysis of variance for vessel area (µm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	1193198.408	596599.204	0.07^{ns}
GIRTH(ZONE)	6	49564925.90	8260820.983	1.67^{ns}
Error	18	88200247.34	4900013.741	
Total	27	138958371.6		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

29. Analysis of variance for vessel length (μm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	347.148	173.574	1.78 ^{ns}
GIRTH(ZONE)	6	584.570	97.428	2.99*
Error	18	585.684	32.538	
Total	27	1517.403		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

30. Analysis of variance for vessel frequency (no. / mm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.074	0.037	0.25 ^{ns}
GIRTH(ZONE)	6	0.889	0.148	1.33 ^{ns}
Error	18	2.000	0.111	
Total	27	2.963		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

31. Analysis of variance for vulnerability index of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	9.645	4.822	0.28 ^{ns}
GIRTH(ZONE)	6	102.448	17.075	1.29 ^{ns}
Error	18	237.424	13.190	
Total	27	349.517		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

32. Analysis of variance for vessel mesomorphy of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	379239.196	189619.598	0.22 ^{ns}
GIRTH(ZONE)	6	5244132.369	874022.062	1.13 ^{ns}
Error	18	13925939.85	773663.325	
Total	27	19549311.41		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

33. Analysis of variance for ray width (µm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	118.286	59.143	1.39 ns
GIRTH(ZONE)	6	254.755	42.459	36.98*
Error	18	20.667	1.148	
Total	27	393.708		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

34. Analysis of variance for ray height (µm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	2854.491	1427.246	1.29 ns
GIRTH(ZONE)	6	6595.998	1099.333	2.41 ns
Error	18	8193.211	455.178	
Total	27	17643.700		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

35. Analysis of variance for ray frequency (no. / mm) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.074	0.037	1.00 ns
GIRTH(ZONE)	6	0.222	0.037	1.00 ns
Error	18	0.667	0.037	
Total	27	0.963		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

36. Analysis of variance for vessel percentage of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.078	0.039	0.85 ns
GIRTH(ZONE)	6	0.275	0.046	2.63 ns
Error	18	0.314	0.017	
Total	27	0.666		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

37. Analysis of variance for parenchyma percentage of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.202	0.101	0.42^{ns}
GIRTH(ZONE)	6	1.468	0.245	1.09^{ns}
Error	18	4.016	0.223	
Total	27	5.686		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

38. Analysis of variance for fibre percentage of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.122	0.061	0.04^{ns}
GIRTH(ZONE)	6	1.534	0.256	1.30^{ns}
Error	18	3.531	0.196	
Total	27	5.186		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

39. Analysis of variance for ray percentage of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.013	0.007	0.24^{ns}
GIRTH(ZONE)	6	1.159	0.193	7.41*
Error	18	0.469	0.026	
Total	27	1.640		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

40. Analysis of variance for modulus of rupture (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	279528.976	139764.488	2.63^{ns}
GIRTH(ZONE)	6	317956.072	52992.679	1.24^{ns}
Error	18	767044.786	42613.599	
Total	27	1364529.834		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

41. Analysis of variance for maximum load (kg) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	10280.716	5140.358	2.62 ns
GIRTH(ZONE)	6	11793.764	1965.627	1.26 ns
Error	18	27967.159	1553.731	
Total	27	50041.640		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

42. Analysis of variance for Modulus of Elasticity bending (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	1006434739	503217369.7	1.63 ns
GIRTH(ZONE)	6	1844674345	307445724.1	1.08 ns
Error	18	5125602172	284755676.2	
Total	27	7976711256		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

43. Analysis of variance for horizontal stress at maximum load (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	358.103	179.052	2.62 ns
GIRTH(ZONE)	6	408.669	68.112	1.25 ns
Error	18	979.946	54.441	
Total	27	1746.719		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

44. Analysis of variance for horizontal stress at limit of proportionality (kg/cm^2) *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	138.799	69.400	4.07 ns
GIRTH(ZONE)	6	102.143	17.024	0.45 ns
Error	18	673.449	37.414	
Total	27	914.390		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

45. Analysis of variance for fibre stress at limit of proportionality (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	108434.023	54217.011	4.10 ns
GIRTH(ZONE)	6	79279.309	13213.218	0.45 ns
Error	18	527756.195	29319.789	
Total	27	715469.526		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

46. Analysis of variance for tensile strength at maximum load (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	67941.716	33970.858	0.53 ns
GIRTH(ZONE)	6	387732.847	64622.141	1.43 ns
Error	18	810119.148	45006.619	
Total	27	1265793.712		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

47. Analysis of variance for compression parallel to grain at limit of proportionality (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	12703.395	6351.698	0.64 ns
GIRTH(ZONE)	6	60082.524	10013.754	1.41 ns
Error	18	127443.410	7080.189	
Total	27	200229.329		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

48. Analysis of variance for compression parallel to grain at maximum load (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	21442.399	10721.200	1.00 ns
GIRTH(ZONE)	6	64476.287	10746.048	1.31 ns
Error	18	146775.178	8154.177	
Total	27	232693.864		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

49. Analysis of variance for Modulus of Elasticity compression parallel to grain (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	82894230.93	41447115.47	0.51 ^{ns}
GIRTH(ZONE)	6	486258509.0	81043084.84	1.09 ^{ns}
Error	18	1411501545	78416752.50	
Total	27	1980654285		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

50. Analysis of variance for compression perpendicular to grain at limit of proportionality (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.068	0.034	3.09 ^{ns}
GIRTH(ZONE)	6	0.067	0.011	0.78 ^{ns}
Error	18	0.258	0.014	
Total	27	0.393		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

51. Analysis of variance for compression perpendicular to grain at 2.5 mm (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.090	0.045	3.00 ^{ns}
GIRTH(ZONE)	6	0.088	0.015	1.36 ^{ns}
Error	18	0.195	0.011	
Total	27	0.373		

(*) significant at 0.05 level; (ns) non significant at 0.05 level

52. Analysis of variance for Modulus of Elasticity compression perpendicular to grain (kg/cm^2) of *Artocarpus heterophyllus* wood

Source of Variation	df	Sum of Squares	Mean Sum of Squares	F-calculated
ZONE	2	0.064	0.032	10.66*
GIRTH(ZONE)	6	0.018	0.003	0.30 ^{ns}
Error	18	0.182	0.010	
Total	27	0.264		

(*) significant at 0.05 level; (ns) non significant at 0.05 level