EVALUATION OF WOOD QUALITY OF SELECTED TROPICAL PINES RAISED IN THE HIGH RANGES OF KERALA, FOR PULP AND PAPER MAKING

By

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THESIS

Submitted in partial fulfillment of the
requirement for the degree

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DECLARATION

I hereby declare that this thesis entitled **"Evaluation of wood quality of selected tropical pines raised in the high ranges of Kerala, for pulp and paper making"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

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DEDICATED TO

MY PARENTS & TEACHERS

Introduction

1. INTRODUCTION

Pines are the most important group of timber trees in the world. They belong to the genus *Pinus* and family *Pinaceae*. More than half the species of *Pinaceae* and almost 20 per cent of all gymnosperm species are included in the genus *Pinus*. There are about 232 species (Frankis, 1989), the exact number being a matter of dispute among botanists mostly distributed in temperate regions, but a few occur in the tropical and subtropical climates of the West Indies, Central America, the Philippines, and south eastern Asia. About 63 per cent of pine species are found in America, amongst which the greatest number occur in Mexico.

Pines are well known for their utility from time immemorial. They are valuable sources of timber, fuelwood, pulpwood and NTFPs like resins. Hence, pines have been cultivated very widely in many parts of the world, both within as well as outside their natural range, and they form the foundation of exotic forestry enterprises in many southern hemisphere countries. Pine is, without a doubt, one of the most economically significant tree genus in the world.

Tropical pines grow naturally in the tropical and sub-tropical areas, chiefly in the Mexican plateau, Caribbean islands, southern parts of Burma, Indonesia, Philippines, etc (Fig. 1) (Aung Din, 1958). They are relatively fast growing species, with long fibre that could be used as pulpwood species (Oluwafemi, 2007). They also have good adaptability to wide range of soils and climate and have high productivity and performance, varying with species, provenance, climate and site conditions (Torvi et al., 1998). The rotation length of tropical pines may be as long as 40 years, but King (1975) stated that pine rotation length for pulping in temperate region may be between 30-40 years and could be less in the tropics. All these features make them popular for plantation forestry in the tropics. Interestingly, the lion share of the softwood plantations in the tropics (approximately 75 per cent) are pines. The species tried were *Pinus patula* Schl. et Cham., *Pinus oocarpa* Schiede, *Pinus caribaea* Morelet,

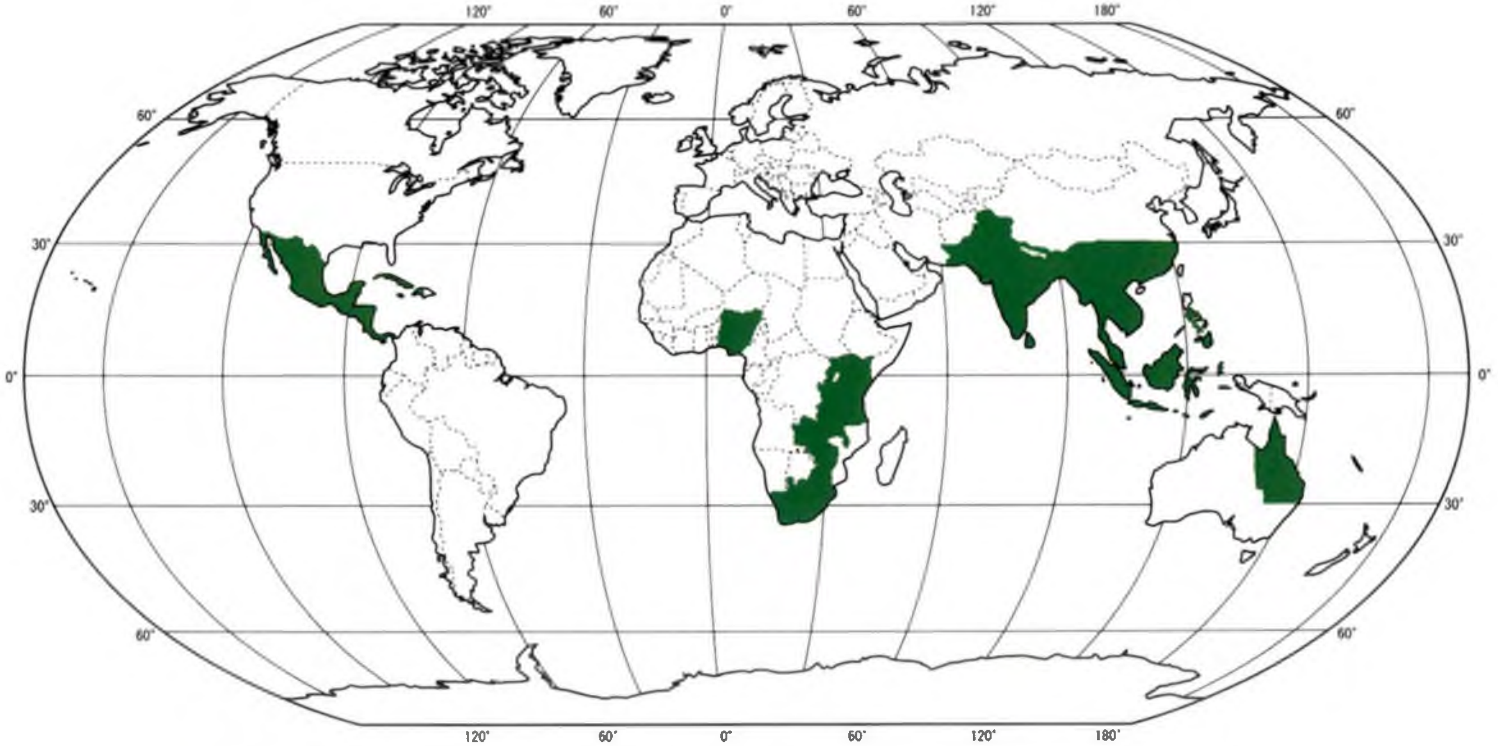

Fig 1. World map indicating the limits of the regions of growth of tropical pines between 30° N and 30° S latitudes

(Source: Aung Din, 1958)

Pinus radiata D. Don, *Pinus insularis* Endl., *Pinus merkusii* Jungh. et de Vr. and *Pinus pseudostrobus* Lindl., etc.

Pinus caribaea (Pino or Ocote) is naturally distributed in Belize, Honduras, Nicaragua, Guatemala, Bahama Islands, Cuba and is widely introduced as a plantation species in countries like Australia and South Africa (Chudnoff, 1984). *Pinus caribaea* is reported to be occurring in the lowland humid tropics (Evans, 2003). It is used for construction works, carpentry, flooring, joinery, plywood, pulp and paper products. The pulp wood of this species is considered good for paper production (Borja et al., 2001).

Pinus patula (Mexican weeping pine) is naturally distributed widely in Mexico in Tamaulipas, Hidalgo, Distrito Federal, Morelos and Tlaxcala (Wormald, 1975). *Pinus patula* prefers the cooler highland tropics and sub-tropics (Evans, 2003). This is also a popular ornamental and agro forestry species in many moist tropical areas, such as South Africa, where it is the most important pine species (Kietzka, 2002).

Natural ranges of *Pinus oocarpa* (Mexican pine) are Mexico, Guatemala, Honduras, El Salvador and North West Nicaragua. It has a wide distribution in Mexico and Central America (Saenz, 2003). It is also introduced into the tropical countries of South and South East Asia (De la Rosa, 1998).

Global demand for wood is increasing at an annual rate of 1.7 per cent (South, 1999). At the same time, planted forest resources are insufficient to meet current demands. The scope for expansion of forested areas is limited (Gregory et al., 2002). This trend creates economic pressure that encourages the commercial exploitation of natural forests unless, supply can be increased through the establishment of higher yielding plantations. The use of fast growing, elite trees enable early harvest and so it helps to improve yield.

In India, planting of tropical pines got impetus in the sixties. The dwindling bamboo resources and the difficulty in the extraction of coniferous wood in the upper Himalayas resulted in shortage of long fibered raw material essential for paper and pulp industries. Tropical pines forged ahead as a popular species to fill the above gap, because of its adaptability to Indian conditions and long fibred nature. Plantations of tropical pines are being raised in various states such as West Bengal, Madhya Pradesh, Maharashtra, Uttar Pradesh, Orissa, Tamil Nadu, Kerala, Himachal Pradesh and Assam. The species used are *Pinus patula, Pinus caribaea, Pinus kesiya* Royle ex. Gordon, *Pinus oocarpa, Pinus merkusii, Pinus elliottii* Engelm., *Pinus pseudostrobus, Pinus greggi* Engelm. and *Pinus radiata.*

Research trials of tropical pines in Kerala

The research wing of the Kerala forest department has initiated several research trials at different locations in the various parts of the state during 1975 to 1986 period, mainly to evaluate their growth performance and as species introduction trials. The trial includes pine species such as *Pinus caribaea, Pinus greggii, Pinsu kesiya, Pinus patula. Pinus oocarpa, Pinus taeda* L., *Pinus elliottii, Pinus patula, Pinus pseudostrobus, Pinus merkusii, Pinus cubensis* Grisebach and *Pinus radiata.* They have been raised by the research division at Peerumedu research range (Idukki), Mananthavady research range (Wayanad) and at Kulathupuzha research range (Kollam) at different locations therein. These trials were initiated from 1975 to 1986 and the age of the trees varies from 35-24 years. The species offers great promise as potential pulp wood species which can be grown in high elevation areas in the state since, being conifers, the wood may be highly suitable for pulping as well as for other wood products such as resin, oils etc.

Wood traits also affect the quality of wood products and these properties are highly variable, with change in environmental conditions. This is of great importance in the case of exotic forestry and the information in this aspect with respect to pines in Kerala is entirely lacking. So the present study focuses on three species such as *Pinus caribaea, Pinus patula* and *Pinus oocarpa.* As these three species of pines have been found to perform reasonably well under the prevailing conditions in the trials undertaken, they need to be tested for their wood properties.

The proposed investigation is intended to bring into light the effect of variation in species, locality and age on the timber quality parameters under the existing eco-climatic conditions prevailing in the state with special reference to their suitability for pulping. The information gathered will be useful for introduction and popularization of the above species in suitable areas of the state by the paper and pulp industries wishing to undertake large scale pulp plantation programmes using these species. The information could be further used in the tree improvement programmes of these species of tropical pines for wood quality.

Objectives:

The objective of the present investigation is to study wood properties such as specific gravity, tracheid morphology, ray morphology, tissue proportion, tissue frequency and chemical properties in three tropical pines viz., *Pinus caribaea, Pinus patula* and *Pinus oocarpa* grown in research trials of the Kerala forest department in the high ranges of Idukki district of Kerala to find out:

1. Species variation in terms of the above characters.
2. Within tree (radial) variation of wood properties at breast height level.
3. Effect of age on the timber properties of the above pine species.
4. Variation in factors like Runkel ratio, shape factor, rigidity coefficient, flexibility coefficient, and slenderness ratio which have application in paper and pulp industries.
5. Establish correlation among the anatomical properties and suggest ways for their usefulness for future wood quality improvements.

Review of literature

2. REVIEW OF LITERATURE

Wood is not a homogenous material. It is highly variable. Generally, all dimensional and physical characteristics of wood within a tree exhibit a high range of variation (Panshin and de Zeeuw, 1980). The variations which are present can be related to radial or axial position of the sample either within an individual growth increment or over a series of growth increments at any given height. This variability in wood characteristics is higher in extent within a single tree than among trees growing on the same site or between trees growing on different sites. This fact of variability in wood has been fully appreciated by some of the investigators in their attempts to secure satisfactory criteria for identification and classification of wood giving due consideration to the range of variation to each of the diagnostic characters (Wilson and White, 1986; Carlquist, 1988; Wheeler et al., 1989).

2.1 THE SOURCES OF VARIATION IN FOREST TREES

Variation in forest trees is usually described in terms of various categories, levels or sources. In a breeding programme, variation is usually defined at a number of levels or sources (Zobel and Talbert, 1984) such as; (i) Species; (ii) Geographic (provenance) variation; (iii) Variation among sites within provenances; (iv) Differences between families within provenances; (v) Differences between trees within families; and (vi) Within trees. A large proportion of the variability in wood properties is under genetic control (Zobel and Jett, 1995). The environment under which a tree grows is also a major driver of variation (Zobel and van Buijtenen, 1989). In majority of cases within tree variation is the largest source of differences in wood and fibre properties due to the fact that various factors within the tree have significant impacts on the fibres produced. Various patterns of variability that exist within a tree (Zobel and van Buijtenen, 1989) are; (i) Within ring differences; (ii) Changes from the centre (pith) to the outside (bark) and (iii) Differences due to different heights.

2.1.1 Importance of understanding variation in wood properties

The knowledge about these variations in wood is of great importance from the utilization point of view. This is because, variation in wood, as a raw material, is a major determinant of the properties of products made from it (Raymond, 2002; Wimmer et al., 2002). Furthermore, the suitability, or quality, of wood for a particular purpose is determined by the variability in one or more of these characteristics which affects its structure and hence its physical properties. For example, minor changes in percentage of cell types and their dimensions, cell wall structure and ratios of cellulose to lignin are important for the assessment of pulp quality. So the variation pattern that exists in wood with respect to species, among age groups within species and variation induced with respect to existing eco-climatic conditions must be understood.

There are numerous studies related to wood properties and causes of wood variation because of its importance. Voluminous literature related to these subjects exist, but it is neither well known nor appreciated by foresters who will ultimately produce wood since the publications are often not available or are not well understood by the forester or by those who use wood. Often the literature is contradictory and confusing (Downes and Raymond, 1997), making it difficult for the user to use the information available correctly (Zobel and Talbert, 1984).

In conifers, it is well known that the first 10 or so growth rings surrounding the pith, a ''corewood'' cylinder, is of inferior quality compared to wood further out. Less desirable characteristics of this corewood cylinder in conifers include the following (Zobel, 1975): (i) low basic density (oven-dry matter) in some key commercial species., (ii) high moisture content before heartwood formation., (iii) moderate to high longitudinal shrinkage., (iv) a lower percentage of cellulose, and (v) Short tracheids (fibers). This will make lightly lower yield of chemical pulp and the paper has low tear strength due to the short fibers. These generalisations are of major relevance for fast grown, short rotation plantations, where the trees are harvested after only 15 to 30 years. In such situations at least half the merchantable wood is this poor-quality corewood. In consequence, as stands are harvested earlier, industry has had to face a steady deterioration in wood quality. This arises from the increased proportion of corewood, further aggravated by a much greater variability that arises from the rapidly changing properties within corewood itself. Fast growth is not the problem; it is rather the abundance of corewood arising from the shorter harvesting cycle (Kennedy, 1995). So a better understanding of the changing quality of the wood from fast-grown plantations is helpful to its efficient processing and utilization.

Fast growing plantations have steadily increased over the decades throughout the world due to well-known reasons. It is expected that the proportion of plantations of both softwoods and hardwoods will continue to increase until it predominates in the next century (Zobel, 1980; Bingham, 1983). As a sequel, changing resources throughout the world would lead to changing quality of wood supply (Zobel, 1984; Senft and Bendtsen, 1985; Zobel and van Buijtenen, 1989).

Much of the recent expansion in plantation forestry is occurring in the tropics and subtropics, where a number of new species such as *P. greggii, P. maximinoi, P. patula, Pinus caribaea* var. *hondurensis*, *P. oocarpa* etc are being tested for its fast growth and other utilitarian characteristics. Compared with temperate wood species, this tropical softwood mature as quickly and can be harvested as pulpwood at a comparatively young age (Twimas et al., 1998). In most cases very little or nothing is known about the wood properties of these new species when they are grown as exotics in plantations. In India, the investigations on tropical pines are carried out only in a limited extent. The probable reason must be the limited distribution of tropical pines in our country as an exotic. So there is a great deal of scope regarding research in wood properties of tropical pines in India. As mentioned earlier, studies on variation of wood properties of these species will be of great use in deciding the efficient utilization of these wood resources.

2.2 WOOD PROPERTIES IMPORTANT TO THE PULP AND PAPER INDUSTRY

Wood properties such as density, anatomical characters and chemical properties play an integral part in determining the pulp or paper quality. To realize the role each of these properties play in the formation of the end product, it is essential that the characteristics of these wood properties be correlated to properties utilized during the production of paper, and properties of the final product. These correlations will then determine the suitability of the tracheids (Barefoot et al., 1964). These relationships not only determine the effect of various tracheid and wood properties on pulp and paper produced from those tracheids, but can also be used to determine the effect of various stand management practices on end-product to predict the pulp properties of improved planting stock.

Utilizing *P. elliottii* for the production of Kraft pulp, Barefoot et al. (1964) investigated a number of correlations and ratios to determine the effect the various properties have on the production of paper. Utilizing multiple regressions, they indicate the best predictor i.e. the trait that accounted for the greatest amount of variation in the paper property and also indicated other characteristics that had significant correlations on hand sheet properties. It has been found that very few characteristics can be utilized as single indicators of hand sheet properties, and these properties are usually an interactive influence of a number of properties (Kibblewhite and Uprichard, 1997).

Excellent literature reviews on the influence of wood properties on pulp and papermaking properties were made by Dadswell and Wardrop (1959), and Dinwoodie (1965). In another study by Barefoot et al. (1964);

and Wangaard (1962) demonstrated strong influence of certain fiber dimensions on pulp and paper properties. Also there is a large volume of literature available on chemical properties of wood and its effect on pulping (Dinwoodie, 1966; Kasprzyk and Wichacz, 2003; Labosky et al., 1984; Malan et al., 1994; and Morais et al., 2005).

2.2.1 Wood density or Specific gravity

The terms density and specific gravity are both used to describe the mass of a material per unit volume. These terms are often used interchangeably although they each have precise and different definitions (Bowyer and Smith, 1998). Both terms are defined by Haygreen and Bowyer, 1996; Zobel and van Buijtenen (1989); and Hoadley (2000). Specific gravity is the ratio between the mass per unit volume of water, while wood density is defined as mass or weight per unit volume of water. In other words, both terms are used to indicate the amount of actual wood substance present in a unit volume of wood and also both terms can be calculated from one another (Zobel and Jett, 1995). Therefore, they will be used interchangeably.

Zobel and Jett (1995) pointed out that wood density is, in fact, not a single wood property but a combination of wood properties (latewood percent, wall thickness, cell size, and others). However, despite its complexity, wood density reacts generally as though it were a single, simple characteristic.

2.2.1.1 Importance of wood density

Wood basic density is considered one of the most important features in genetic improvement programmes (Zobel and Talbert, 1988) and is one of the most often studied wood quality traits (Downes et al., 1997; Peszlen, 1998; Downes and Raymond, 1997; McKinley et al., 2003; Cown et al., 2006; Jordan et al., 2008). This easily assessable property is of key importance in forest product manufacture because it has a major effect on both yield and quality of fibrous and solid wood products (van Buijtenen, 1982).

Wood density can be changed by silvicultural manipulation (Williams and Hamilton, 1961) and genetic manipulation (Zobel, 1961; van Buijtenen, 1962). It is a complex feature influenced by cell wall thickness, the proportion of the different kind of tissues, and the percentages of lignin, cellulose and extractives (Valente et al., 1992). This expresses how much wood substance is present per unit volume, has a significant effect on the quality and yield of pulp and paper products and on strength and utility of solid wood products.

In a species, the wood density is the most important wood characteristic because knowledge about it allows the prediction of a greater number of properties than any other trait (Zobel and Talbert, 1984; Bowyer and Smith, 1998). In addition, it has a major effect on both yield and quality of the final product and it is strongly inherited (Zobel, 1984). Bamber and Burley (1983), state that, of all of the wood properties, density is the most significant in determining the end use of the wood. The specific gravity of wood is its single most important physical property. Most mechanical properties of wood are closely correlated to specific gravity and density (Haygreen and Bowyer, 1996; Walker, 1993). It appears to influence machinability, conversion, strength, paper yield and many other properties (Wimmer et al., 2002).

The selection of a suitable tree species for the pulp and paper industry depends on the specific gravity and yield of wood as well as on the anatomical characteristics of fibres (Dinwoodie, 1966; Wright and Sluis, 1992; Rudie et al., 1994; Brolin et al., 1995). The influence of density extends from transport costs and chipping properties to digester capacity, pulp yield per unit mass of wood, and paper quality (Balodis, 1981). According to de Guth (1960), wood density can be correlated with strength properties of wood, pulp yield and pulp quality. It can also be used as a predictor of yield and quality of pulp and paper products (Dadswell and Wardrop, 1959; Barefoot et al., 1970). High densities are advantageous since they correspond to higher pulp yields on a raw material volume basis, and to a better use of digester capacity (Miranda et al., 2001).

2.2.1.2 Density and wood properties

As was pointed out before, wood specific gravity allows the prediction of a greater number of properties than any other trait. Jerome et al. (2006) reported that wood density is the best single descriptor of wood: it correlates with numerous morphological, mechanical, physiological, and ecological properties. Some wood properties that are closely related to wood specific gravity are: strength, dimensional stability with moisture content change, 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). Wood density is considered as the best single index of wood quality because it is the most dependable characteristic for predicting timber strength (Shirin et al., 1998). Kibblewhite (1980) reported that wood density is more critical than fiber length in deciding the handsheet strength.

A key issue in making paper is bonding of wood elements. Fiber to fiber bonding is very important in a paper sheet, with hydrogen bonding being the single most important factor in connecting fibers. The best wood for manufacturing strong paper is often of low, rather than high, specific gravity (Bowyer and Smith, 1998). Papers made from low-density wood present smoother, high tensile and busting strength characteristics, but low opacity, therefore, they are best suited to packaging products. Conversely, papers made from high-density wood often tend to be bulky, with an open structure, which is porous and more compressible giving the paper better printability and opacity characteristics (Gantz, 2002). Zobel and Jett (1995) pointed out the close relationship between cell wall thickness and wood specific gravity. Increasing wall thickness increased tear strength but reduced tensile strength and burst. High specific gravity is usually preferred over other wood traits because it contributes to strength properties of paper such as tear and contains more mass per unit volume than lower specific gravity woods; that is, it contributes to high yields in pulp. When wood is bought by volume, the greatest quantity of wood fiber in a given volume will be obtained from the highest specific gravity wood (Bowyer and Smith, 1998). Nevertheless, woods with low specific gravity are preferred as a raw material for making high strength wood composite products such as standard particleboard, oriented strand board, and parallel strand lumber.

Wood density is the strongest predictor for handsheet properties (du Plooy, 1980; and Malan et al., 1994). It is related negatively to tensile, burst and tear indices. Denser wood produces bulkier, stiffer and more porous sheets, while low density wood results in smoother, denser sheets, with higher tensile strength. Denser wood also corresponds with increases in light scattering coefficient, opacity (Cown and Kibblewhite, 1982) and paper surface roughness (Scurfield, 1976).

Sheet density (bulk) is strongly linked to wood density (Malan et al., 1994). This sheet density is a measure of fibre collapse, allowing better interfibre bonding. A handsheet is a two-component arrangement, the large fibrous proportion providing bulk or thickness of the sheet. Short fibres and debris contribute mass, but without increasing bulk, and they are deposited in between the longer fibres, improving fibre bonding and thus contributing to burst and tensile strength, usually with a reduction of the tear index (Malan and Arbuthnot, 1995). Freeness of unbeaten and beaten pulp increased with wood density, in accordance with the trend reported by Vasconcellos Dias and Claudio-da-Silva (1985).

The salient research findings of wood density or specific gravity studies conducted in pines with respect to species, age and radial variation are summarized hereunder.

2.2.1.3 Wood density variation in softwoods

Most commercial softwoods have oven-dry densities that lie between 400 and 600 kg/m^3 implying that the cell wall occupies on an average about one-third of the volume and that the other two-thirds are available for sap in the living tree or is occupied by air when cut and dried as lumber (Huang et al., 2003). Several authors such as Bryce (1967), Lamb (1973), and Plumptre (1984) report that the density of *P. caribaea* is quite variable. Plumptre (1984), for example, reports a coefficient of variation of 13.2 per cent for material grown in Fiji.

Thinning effect on wood density and ring width in *Pinus patula* stands was evaluated by Gorche et al. (2003). Each sample was analysed as to wood density and basic density of growth rings. Both site quality and thinning did not influence wood density. Absolute wood density values were 0.45 and 0.44 g/cm^3 for high site quality before and after thinning, respectively, while in low site quality, absolute wood density values were 0.47 and 0.44 g/cm^3, before and after thinning, respectively. Thinning did not affect wood density because variation is present in early years of growth.

Wright and Malan (1991) examined the variation in wood and tracheid properties of *Pinus patula* along with two other pines. It was reported that the *Pinus patul*a trees of 10.5 years age were having a mean air dry wood density of 444 kg/m^3 which ranges from 421 kg/m^3 to 484 kg/m^3.

A study to examine the effect of environment on wood density and pulp quality of five pine species grown in Southern Africa was done by Clarke et al. (2003). Wood density, pulp yield and burst strength were the properties that best distinguished between the five species of pines.

Pinus elliottii had high density but low pulp yield while *Pinus patula* and *Pinus maximinoi* had high yield but low density and *Pinus taeda* and *Pinus kesiya* had yields in between *Pinus elliottii* and *Pinus patula*, but had low density.

Mendes et al. (1999) reported on the longitudinal variation on wood density of *Pinus oocarpa.* Variation of the wood basic density along the stem of 14 year-old trees planted at Minas Gerais, Brazil were evaluated. The basic density of the wood discs was determined by the maximum moisture content method and the tree mean density by the weighted mean method. The mean basic density was 0.446 g/cm3. The basic density decreased with height in *Pinus oocarpa.* In another study Hannrup et al. (2001) investigated the relationships between wood density and tracheid dimensions in *Pinus sylvestris.* The results showed that earlywood radial and tangential lumen diameter and latewood proportion showed the strongest correlations with wood density. Multiple regression analyses indicated that earlywood radial lumen diameter and latewood proportion were the two most important predictors of wood density.

Wood density of radiata pine (*Pinus radiata*) and factors affecting it were studied by McKinley (1997). The data from radiata pine stands sampled throughout New Zealand confirmed an earlier work showing mean annual temperature as the major environmental factor affecting wood density. To explore the extent to which wood density could be estimated for rare or poorly censused taxa and possible sources of variation in this trait, Jerome et al. (2006) analyzed regional, taxonomic, and phylogenetic variation in wood density among 2456 tree species from Central and South America. This study revealed that wood density varied over more than one order of magnitude across species, with an overall mean of 0.645 g/cm^3.

Wood formation from the base to the crown in *Pinus radiata* with gradients of tracheid wall thickness, wood density, radial growth rate, and gene expression was estimated by Sheree et al. (2006). Among the results cell wall thickness showed an overall correlation coefficient of > 0.7 with wood density. In another study Malan (2001) analyzed wood quality of fifty trees of *Pinus chiapensis*. They had an average air-dry density of 0.420 g/cm^3 (extracted and at 12 per cent moisture content) with individual tree densities varying from 0.380 to 0.465 g/cm^3 at 0.8 m height level.

Wood density and microfibrillar angle in *Pinus radiata* clones were analysed by Cown et al. (2004). Properties assessed included wood density, microfibril angle, spiral grain, and incidence of compression wood. Wood density values differed markedly between clones, but within each the overall patterns of density variation were consistent from pith to bark and between stem levels, indicating high heritability. The major factors contributing to twist were spiral grain and density.

Basic wood features like wood density, annual ring width, sapwood percentage, latewood percentage of Scots pine (*Pinus sylvestris*) trees from the forests in the Carpathian and Sudetes areas of Poland were studied by Niedzielska et al. (2001). Doruska et al. (2006) estimated variation in wood density by stand origin and log position for loblolly pine sawn timber in the Coastal Plain of Arkansas. Repola (2006) investigated on the vertical dependence of the basic density of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and birch (*Betula pendula* and *Betula pubescens*) stems, and how such dependence could be applied for determining the average stem wood density.

Gutierrez et al. (2006) studied the effect of growth conditions on wood density of *Pinus nigra.* The results lead to the conclusion that there is no significant relationship between extracted wood basic density and provenance or growth rate.

The wood density, annual ring width and latewood content in five different species of larch (*Larix spp.*) and in Scots pine (*Pinus sylvestris*) were investigated using direct scanning X-ray densitometry by Karlman et al. (2005). The variation in density between different trees of the same species was big. Average wood density of larch trees was 618 kg/m^3 in old Siberian larch and 621 kg/m^3 in mature European larch timber grown in Sweden. Corresponding figures for mature Scots pine was 504 kg/m^3.

Kang et al. (2004) reported the effects of initial spacing on wood density, fibre and pulp properties in jack pine (*Pinus banksiana*). The results clearly show that initial stand spacing has a significant effect on all of these properties, and thus it is possible to improve yield and wood pulp fibre properties of jack pine through stand density regulation. Non-destructive testing of wood for prediction of strength is significantly influenced by wood density and moisture content. Johansson et al. (2003) predicted moisture content and density of Scots pine (*Pinus sylvestris*) by microwave scanning of sawn timber. The result shows that it is possible to predict both moisture content and density with very high accuracy using microwave sensors.

Bouffier et al. (2003) estimated wood density and hydraulic properties of Ponderosa pine from the Willamette valley versus the same species from that of the Cascade mountains. Earlywood in Ponderosa pine which transports most of the water shows substantial density differences between geographic regions. An invesigation on the variation of wood density and tracheid morphological characteristics of *Pinus densiflora* in different stands conducted by Jin et al. (2001) revealed that there was a significant difference in wood basic density and tracheid width between pure forest and mixed forest. The wood basic density in pure forest was higher than that in mixed forest. The wood tracheid width in mixed forest was bigger than that in pure forest.

Technological characteristics studies of wood of *Pinus caribaea* was carried out by Borja et al. (2001) with 88 trees of *Pinus caribaea* var. *hondurensis* from a forest plantation located in Oaxaca, Mexico. The proportion of latewood, basic density and radial and tangential shrinkage increase as the distance from the pith does, however at higher heights in the stem, the density and radial shrinkage tend to diminish, and the anisotropic relationship of shrinkage was low.

The variation in basic density of *Pinus caribaea* grown in Zanzibar, United Republic of Tanzania was carried out by Khirai and Iddi (1991). They reported that mean basic density for 12 year old *P. caribaea* grown at Masingini forest reserve was 460 kg/m^3 with a standard deviation of 66 kg/m^3. The basic density between trees varied from a minimum of 345 kg/m^3 to a maximum of 637 kg/m^3. Generally, basic density was found to increase from pith to bark. The increase from inner to middle core was slight while the increase from middle to outer core was sharp. Also, growth rate had no significant effect on tree basic density.

Palmer et al. (1984) reported a value of less than 388 kg/m^3 for 12 year old *P. caribaea* grown at Rubya (altitude 1200 m.s.l.). Many of the researchers agree with the fact that the basic wood density shows an increasing trend from pith to bark in many coniferous species (Lema et al., 1978; Ringo and Klem, 1980). It is also known that generally in conifers density varies directly with age (Panshin et al., 1964). Wood density characterization in plantation grown *Pinus caribaea* and its relationship with tree age was estimated by Onilude and Oluwadare (2000). Basic density of the sampled species exhibited significant radial increase from the pith towards the cambium. The mean basic density varied from 402 kg/m^3 at the pith area to 603 kg/m^3 towards the bark with an overall average of 518 kg/m^3. Prediction models were constructed using quadratic equations for estimating basic density.

Oluwadare (2007) reported that basic density increased with age as well as tracheid length and cell wall thickness. They documented the wood properties, basic density and tracheid dimensions, of Caribbean pine (*Pinus caribaea* Morelet) grown in Afaka, Nigeria. The materials investigated in that study were woods from five age series viz., 5, 7, 15, 20 and 25 years. The mean wood basic density recorded was least, 407 kg/m^3, in trees of age 5 and highest, 497 kg/m^3, in trees of age 20 years.

2.2.1.4 Variation in wood density of softwoods with age

In their review of wood variation, Zobel and van Buijtenen (1989) concluded that there is a strong positive correlation between age and wood density for the first 20 years but the correlation is not nearly so pronounced from 20 years onwards. According to Barnes et al. (1999), density rises with age and falls with altitude with almost perfect regularity in *Pinus elliottii*. In *P. patula* density also rises regularly with age but it is virtually unaffected by altitude. This trend of density rises with age in pine species was also reported by Palmer et al. (1984); and Clarke et al. (2003). This was also reported by Muneri and Balodis (1998) in their studies on wood properties of *Pinus patula* grown in Zimbabwe. They found out that wood density differs substantially due to age effect and it critically affects the utilization of wood.

Wood density and tracheid length increased with growth ring age, with a rapid increase occurring in the first 14 years for wood density and in the first 10 years for tracheid length. Radial increase for the whole stem, for all the trees, was about 50 per cent for density and 250 per cent for tracheid length. Age had a dramatic effect on wood density and tearing strength with older trees providing higher values. Increasing age had a deleterious effect for tensile wood properties in *P. elliottii* at low altitude. Age and elevation had a slight influence on density accounting for 25 per cent of the variation but otherwise the influences of environmental variates were weak (Clarke et al., 2003).

Wood density is also influenced by altitude effect. There is a tendency for the species to have higher density at lower altitude. Palmer and Ganguli (1982) for example found that *P. caribaea* had a basic density of 548 kg/m^3 at a site at sea level while two montane sites had basic density of 467 and 377 kg/m^3 respectively. Furthermore, Silinge and Iddi (1990) found that 19 year old *P. caribaea* grown at Kondoa, Central Tanzania at an altitude of 1300 m had basic density of 403 kg/m^3. Lamb (1973) considers that *P. caribaea* with basic density of less than 400 kg/m^3 has low strength properties not suitable for constructional purposes.

Increase in wood density with tree age is due to an increased proportion of denser latewood. In softwoods, because of the uniformity of wood structure, density is largely a reflection of tracheid wall thickness. In species with distinct growth rings, such as *P. patula,* thick-walled latewood is denser than thin-walled earlywood. Consequently the average density is controlled by the ratio of these two types of wood. The proportion of latewood increases with distance from pith and with tree age. In 45 year old *P. patula,* the latewood percentage in ring two was 5 per cent, increasing to 26 per cent in ring 30 (Burley et al., 1970). In *P. radiata* the increase may be from 10 per cent at the pith to 50 per cent in the outerwood (Cown, 1989).

2.2.2 Wood anatomical properties

It was the work of Sanio (1872) on Scots pine (*Pinus sylvestris*) that opened new vistas in the field of wood anatomy, especially in the area of wood anatomical variation. His work prompted many researchers to search for the reasons for wood variation and their application in timber utilization in general and tree improvement in particular (Panshin and de Zeuw, 1980; Zobel and van Buijtenen, 1989). However, results have often been contradictory. One of the studied fiber properties related to paper strength properties was fiber length. Several investigators have found that fiber length directly affects the tensile strength of paper (Arlov, 1959; Barefoot et al., 1964; Dadswell and Wardrop, 1959). This led to the conclusion that hardwood pulps are lower in paper strength properties because the fibers of hardwoods are shorter than those of softwoods. However, several investigators have found contradicting evidence that suggests fiber length does not have a great influence on paper properties, especially on tensile strength (Alexander and Marton, 1968). Watson et al. (1952) showed that *Pinus radiata* handsheet properties depend upon certain structural features of the constituent fibres. A subsequent series of papers discussed the influence of fibre length, latewood proportion, the ratio of fibre length to diameter and microfibril angle (Watson and Dadswell, 1961; 1962; 1964a; 1964b).

In terms of pulping characteristics, the earlywood and latewood of softwoods have been reported to be more different from one another than two entirely different species (Labosky and Ifju, 1972). The effects of growth ring widths and latewood proportions on papermaking properties have been central to several studies (Jones et al., 1966; Gladstone et al., 1970; Labosky and Ifju, 1981; Labosky et al., 1984). The effects of fibre size and shape on paper properties have been investigated for some time (Haywood, 1950; Einspahr, 1964; Dinwoodie, 1965; 1966). More recently, statistical relationships between wood and pulp/paper properties have been developed for *Pinus radiata* (Cown and Kibblewhite, 1980; Kibblewhite et al., 1997) and *Pinus elliottii* (Farrow et al., 2000). Some of the relationships between wood and paper properties, originally developed for conifers, have also been found to apply for hardwoods (Amidon, 1981). Later, Malan et al. (1994) used multiple regression analysis to describe pulp and paper properties in terms of the physical and anatomical properties of wood. The main purpose was to find simple ways of screening trees for pulp and paper properties in breeding programmes. The regression models used by Malan et al. (1994) did not include covariance between the nominally 'independent' parameters and a generalized model has not yet been developed. Tearing resistance is another paper property with correlations established to one or more of the morphological properties of fibers (Clark, 1942; Wangaard, 1962; Watson and Dadswell, 1961). Again, conflicting evidence on importance of fiber length and other properties has been presented by Nelson et al. (1961), and Peteri (1952).

Properties of pulp and paper are, to a large extent, determined by the dimensions of the tracheids or fibers in the wood used (Paavilainen, 1988). For that reason, measurement of tracheid dimensions is important in pulp characterization (Heikkurinen et al., 1990). Softwood tracheids, which are generally longer than hardwood fibers, are often utilized for strength and stability. They form a strong web in the center of the paper, while hardwood fibers are added to the surface, contributing to the papers optical properties (Glomb and Mulligan, 1989). For many purposes, it is desirable to use the longest softwood tracheids available, since there is a positive correlation between tracheid length and paper strength properties, at least up to a certain threshold value (Paavilainen, 1988; Zobel and van Buijtenen, 1989). On the other hand, for some products or processes (e.g. with demand for optimal pulp formation or high surface smoothness) short tracheids might be more useful (Piirainen and Paavilainen, 1986; Kerekes and Schnell, 1995).

An optimization of wood use in the pulp and paper industry should be striven for, and could be attained, if tracheid and fiber dimensions were known for each batch of wood being fed into the industry. Since even within one species there are large variations in tracheid and fiber dimensions between trees, stands, and regions, (Zobel and van Buijtenen, 1989), an increased knowledge of these variations prior to tree felling is needed to optimize wood use. To increase our knowledge of these variations, suitable tools to measure tracheid and fiber dimensions on standing trees are necessary.

Changes in the cambium as it ages, genetic controls that govern the form and growth of the tree, and environmental influences like seasonal or geographical conditions or nutrients supplies are the several factors which will influence the measurable variables in wood. The modifications caused as such of the basic patterns for variance of wood may be independent of, but within the trees have genetic potential (Panshin and de Zeeuw, 1980; Zobel and Talbert, 1984).

Stimulation of the tree growth rate affects the formation of wood and hence, its technological and anatomical properties (Senft and Bendtsen, 1985; Bendtsen and Senft, 1986; Keith and Chauret, 1988; De Kort et al., 1991). The use of tracheids from fast grown trees in the paper industry can thus induce significant changes in paper properties because of the relationships of tracheid length with strength properties of paper such as tensile, bursting, tearing, and folding (Clark, 1962; Smook, 1988; Corson, 1991).

Radial increment cores are often used to determine growth rate and wood density. Since the use of cores constitutes a cost efficient and non-destructive sampling method, it is convenient to measure tracheid length with cores. However, since cores normally are oriented horizontally in the tree, while tracheids are vertically oriented, it is likely that a great proportion of tracheids will be cut in the sampling process. A smaller core diameter will result in a greater proportion of damaged tracheids. If tracheids are measured without regard to damage, the result will be an underestimation of actual mean length. Even if only undamaged tracheids are chosen for measurement, the result may be an underestimation of actual mean length, since long tracheids will have a greater probability of breaking in the sampling process (Hart and Harley, 1967).

When tracheid length is measured from chips, the effect of broken tracheids is usually small (Hartler and Stade, 1979). However, this measurement generally necessitates felling the tree. When increment cores are used, it is normal to use a large diameter core, often 10 mm or more, and only measure lengths of unbroken tracheids. Another method to deal with the problem of broken tracheids was proposed by Polge (1967). By taking a 5 mm core at an angle of 30° to the horizontal direction and cutting out the central part of the core for tracheid length measurement, it was possible to double the share of unbroken tracheids compared to a 10 mm radial increment core. However, this method increases handling time and measurement costs.

2.2.2.1 Fibre morphology of softwoods

The successful conversion of pulp into a marketable product depends on a combination of original fiber properties (fiber morphology) and the response of the fibers to processing variables. Because of the great variety of wood types within the softwood genera, the physical properties of a piece of paper from one species will often vary markedly from a similar piece from another species although processing conditions may have been identical.

The structure of wood is directly responsible for many of the properties which in turn decide quality of wood for specific end uses, pulp and paper being one of them. Among the four cell types of the wood, various aspects of fibre morphology play a significant role in determining pulp and paper characteristics. Wood properties vary within trees, between trees, between stands and regions (Zobel and van Buijtenen, 1989). Increased uniformity and thus greater utility is by itself an objective. A number of studies have been made on different species of woods to find out the correlations between various aspects of fibre parameters.

Tracheid dimensions of conifers have been a subject of investigation throughout the world for over a century (Sanio, 1872; Hartig, 1892; Gerry, 1915, 1916; Anderson, 1951). Fibre length is an important determinant of paper strength, particularly tear, and paper machine runnability (Watson and Dadswell, 1961; Dinwoodie, 1965; Jackson, 1988). The effects of various wood and fibre properties on paper properties have been studied intensively over several decades. In conifers, the trend in tracheid length caused by maturation of the cambium is well known, i.e., tracheids are short near the pith and their length increases at a decreasing rate from the pith outwards (Panshin and de Zeeuw, 1980; Zobel and van Buijtenen, 1989). It is also reported that, from pith to bark, tracheid length increases rapidly and non-linearly during the juvenile period of the tree, and then more gradually in the mature wood (Dinwoodie, 1961; Seth, 1981; Taylor and Burton, 1982; Baas et al., 1986; Frimpong-Mensah, 1987). Within a growth ring, tracheid length increases from early wood to latewood (Chalk and Ortiz, 1961; Seth and Jain, 1976; Seth et al., 1987). Tracheid length is also related to the growth rate of a tree and is thus influenced by environmental factors and depends on the tree's genotype (Makinen et al., 2002; Jaakkola et al., 2005).

In most of the studies on the within-ring variation, differences in tracheid length were examined between earlywood and latewood (Lee and Smith, 1916; Resch and Bastendorff, 1978; Fujiwara and Yang, 2000). According to the comprehensive review of Dinwoodie (1961), tracheids are generally considered to be longer in latewood than in earlywood. However, Gerry (1916) found the opposite for longleaf pine (*Pinus palustris* Mill.) and Douglas-fir (*Pseudotsuga menziesii).* Furthermore, Jackson and Morse (1965) found no differences in average tracheid length between earlywood and latewood for loblolly pine (*Pinus taeda* L.), slash pine (*P. elliottii* Engelm.) and shortleaf pine (*P. echinata* Mill.).

There are only a few studies, partly contradictory to each other, reporting the gradual change in tracheid length from earlywood to latewood within an annual ring. Bisset and Dadswell (1949), Amos et al. (1950), Bisset et al. (1951), and Kramer (1957) suggested that the shortest fibres are in earlywood corresponding to the period of maximum radial growth rate and the longest fibres in the last-formed latewood corresponding to the period of minimum radial growth rate. In contrast, Jackson and Morse (1965), and Sub and Muller (1970) found the longest tracheids near the transition from early wood to latewood, and thereafter a decrease at the end of latewood. Taylor and Moore (1981) concluded that in loblolly pine, earlywood tracheids are not consistently longer or shorter than latewood tracheids. In juvenile wood, first formed earlywood tracheids were the shortest, but in mature wood the first formed earlywood and the last formed latewood tracheids were of the same length (Taylor and Moore, 1981).

On an average, tracheids of Scots pine were 0-17 per cent longer in latewood than in earlywood (Bisset and Dadswell, 1950). In this study, no significant differences between earlywood and latewood were found for Norway spruce. In a much earlier study, Mork (1928) found that tracheids were on an average 13 per cent longer in latewood than in earlywood for Norway spruce. Schulze-Dewitz (1959) and Kennedy (1966) reported that there was an increasing trend across the ring resulting in an average difference of 15-25 per cent between earlywood and latewood for Norway spruce. Recently, Makinen et al., (2002) found a slightly lower difference (11 per cent) between the lengths of latewood and earlywood tracheids for Norway spruce. For other conifer species, latewood tracheids have generally been longer than in earlywood. According to Kribs (1928), the tracheids of jack pine (*Pinus banksiana* Lamb.) were 1-3 per cent longer in latewood than in earlywood. Chalk (1930) found that the tracheids of Sitka spruce (*Picea sitchensis*) were approximately 12 per cent longer in latewood than in earlywood.

Anderson (1951) reported that latewood tracheids of white fir (*Abies concolor* Gord.) were 7 per cent longer. Furthermore, Goggans (1962), and McMillin (1968) found that tracheids of loblolly pine were 6-15 per cent longer in latewood than in earlywood. In eight gymnosperms, Bisset and Dadswell (1950) also found that latewood tracheids were longer, i.e., the length difference between latewood and earlywood tracheids was 0-12 per cent.

However, results contradictory to the increasing trend of tracheid length from earlywood to latewood have been published. In an early study of longleaf pine and Douglas fir, the earlywood tracheids were longer than latewood tracheids (Gerry, 1916). Jackson and Greene (1957) found no significant differences in average tracheid length in earlywood and latewood of slash pine. Accordingly, Jackson (1959), and Jackson and Morse (1965) reported that there was no significant difference in average tracheid length in earlywood and latewood of loblolly, slash and shortleaf pine. Ollinmaa (1958) also found that there was no clear difference in fibre length of downy birch (*Betula pubescens* Ehrh.) between earlywood and latewood. No obvious and biologically plausible explanation is readily available for the different studies.

Tracheid length is often greater in wood with low growth rate compared to rapid growth rate (Frimpong-Mensah, 1987), although some contradicting results exist, as reviewed by Zobel and van Buijtenen (1989). Additionally, tracheid length tends to be longer in mature wood compared to juvenile wood (Taylor et al., 1982; Zobel and van Buijtenen, 1989; Yang and Hazenberg, 1994).

Seth and Page (1988) have shown that, under certain conditions, tearing resistance depends strongly on fiber length, whereas Horn (1978) reports that increase in raw material fiber length enhances the tearing strength of hardwood pulps. Using multiple regression analysis, Horn and Setterholm (1990) also found that the majority of variation in burst and tensile strength in hardwood pulp sheets could be accounted for by fiber length and cell wall thickness. Kellogg and Thykeson (1975) and Matolcsy (1975) have also pointed out the significance of fiber dimensions in predicting wood pulp mechanical properties. But in another study it has been reported that the fiber length in softwoods does not show a relationship to any one sheet strength property (Horn, 1978). In the case of hardwood pulps, fiber length can have a significant effect on many sheet properties (Horn, 1978). Bursting strength of sheets made from unbeaten hardwood pulps also show a dependence upon fiber length.

For quality control purposes in industry, pulp is classified according to different fibre length fractions in the mix (Dodd, 1986). However, little is known of how intra-ring frequency distribution of tracheid length changes from pith to bark. As an exception, Hamm (1989) reported that in Douglas fir, the mean tracheid length increased with age across the stem, while the variability increased dramatically. Although the major patterns of radial and vertical variations in wood quality are known to be related to long-term growth effects (Frimpong-Mensah, 1987), controversy exists about the effects of increased growth rate on tracheid length and the relationship of mean tracheid length with ring width. Generally wider growth rings were associated with lower mean tracheid length (Dinwoodie, 1965). But this contradicts with the results reported by Zobel and van Buijtene (1989).

Strong correlations between fibre length and tear index have been reported for both hardwoods and softwoods (Watson and Dadswell, 1961; du Plooy, 1980; Labosky and Ifju, 1981; Malan et al., 1994). In handsheets made from beaten pulp, fibre bonding increases. In addition to fibre length, wood density played a direct role in predicting tear index. At higher sheet densities, interfibre bonding goes up and fibre length has stronger effects on tear index. Longer fibres have a greater total number of bonds per fibre at a given sheet density. Fibre length also had a significant positive effect on freeness at both beating levels. The water in pulp with longer fibres drains more rapidly, which is an important property during paper formation especially with the increased use of recycled fibres that tend to have much lower drainage rates than virgin fibres.

A work on anatomical structure and quantification of the wood of *Pinus oocarpa* was carried out by Tomazello (1987). He concluded that compression wood of this species was characterized by rounded tracheids with intercellular spaces and showed invaginations and helical cavities in tracheid cell walls; tracheids were shorter, narrower, with thicker walls than those of normal wood.

In another study conducted by Ringo and Klem (1989) on the effect of ring width on density and tracheid length in the wood of *Pinus patula,* results showed that tracheid length was significantly and positively correlated with ring width in only one year. Ishengoma et al. (1995), studied basic density and tracheid length of normal and compression wood from plantation grown *Pinus patula* and reported that mean tracheid length of normal wood was 4.6 mm ± 0.3 mm while that of compression wood on the opposite side was 3.4 mm ± 0.2 mm; and tracheid length in compression wood was on an average 35 per cent shorter than in normal wood. While both tracheid length and coarseness affect paper smoothness and strength, variation in the former is generally investigated because it is easier to obtain good estimates and it has been demonstrated in the past that both are highly correlated (Clark 1962; Sastry and Wellwood, 1974).

Studies have also shown that tracheid length varies within trees from stump to crown (Wang and Micko, 1984) and from earlywood to latewood, with the latter having longer tracheids (Bannan, 1965). Hence, tracheid lengths generally are at a minimum within the earlywood zone, increases within the latewood zone, and then decreases at the end of the annual ring. A study was undertaken by Wright and Malan (1991) on variation in wood and tracheid properties of *Pinus maximinoi, P. pseudostrobus* and *P. patula* and reported that significant differences were found within species for the wood and tracheid properties, which suggests that these traits can be altered through silvicultural techniques, genetic manipulation or a combination of the two. The *Pinus patula* trees of 10.5 years age showed an average wall thickness of 6.47 μm and lumen diameter of 26 μm.

In a study done by Wright and Sluis (1992) on the tracheid morphology and pulp and paper strength traits of *Pinus taeda* and *P. patula* at age 17 years in South Africa, slight differences between the two species for pulp and paper strength and tracheid characteristics was observed. No single tracheid characteristic could account for more than 50 per cent of the observed variation. Pande et al., (1995) studied variation in the dimensions of tracheid elements of *Pinus caribaea* var. *bahamensis* and concluded that the earlywood tracheid dimensions were found to be significantly different from those of latewood at different heights.

Ishengoma et al., (1995) conducted a study on basic density, tracheid length and strength properties of juvenile and mature wood of *Pinus patula* grown in Tanzania and reported that juvenile wood had lower basic density, shorter tracheid length and inferior strength properties in comparison with mature wood. Vasquez (1998) studied variations in anatomical characteristics and wood density of *Pinus caribaea var. hondurensis* in relation to tree spacing and observed that the longest tracheids were detected from the 3rd to the 7th growth ring, with shorter tracheids until the 10th growth ring. Great changes were found in tracheid width, tracheid diameter, and the lumen and wall thickness of tracheids of the first 7 growth rings, as well as clear differences between early and latewood tracheids in all growth rings.

Beaulieu (2003) studied the genetic variation in tracheid length and relationships with growth and wood traits in eastern white spruce (*Picea glauca*) and found that more than 90 per cent of the variation in tracheid length is due to differences among trees within plots and only 4.5 per cent is due to variation among families. Also, tracheid length does not appear to be related to wood specific gravity (ages 17 to 21), but is negatively correlated to growth traits. Hence, a selection in favor of volume would cause a decrease in tracheid length.

Clones with higher fibre length, lower vessel diameter and higher vessel frequency have higher strength properties. On the other hand, clones with higher vessel length; higher vessel diameter and lowest vessel frequency have lower strength properties (Vimal et al., 2005). Geographic variations in white spruce (*Picea glauca*) growth and adaptive traits have been thoroughly investigated in the past (Khalil, 1985; Genys, 1986).

Within tree variation of tracheid characters was studied for 14 and 25 year old *Pinus patula* trees grown at two plantation sites in Zimbabwe by Muneri and Balodis (1998). The 25 year old trees had longer tracheids than 14 year old trees (355 mm and 384 mm against 348 mm and 307 mm). The tracheid length increased with growth ring age, with a rapid increase occurring in the first 10 years for tracheid length

The derived values such as slenderness ratio, flexibility coefficient, rigidity coefficient, shape factor and Runkel ratio are useful tools in predicting the suitability of various raw plant materials for papermaking (Saikia et al., 1997; Ogbonnaya et al., 1997; Uju and Ucwoxe, 1997; Yáñez-Espinosa et al., 2004). Papers made from materials having good slenderness ratio may thus be suitable for writing, printing, wrapping and packaging purposes (Saikia et al., 1997). But a poor slenderness ratio indicates poor tearing resistance. This is partly because short and thick fibres do not produce good surface contact and fiber to fiber bonding (Ogbonnaya et al., 1997). Strength properties of paper, such as bursting strength and tensile strength, are highly dependent upon fiber to fiber bonding. Generally, bursting and tensile strengths of paper made from softwoods respond to the same fiber characteristics as do hardwoods (Horn, 1974; 1978). This is especially true after the pulps have been beaten. Using length/diameter as a measure of fiber flexibility is an excellent indicator for the potential use of a softwood pulp for paper products requiring high strength (Horn and Setterholm, 1990).

2.2.2.2 Tracheid morphology of softwoods

Sheet density is influenced by fibre dimensions such as diameter and cell wall thickness and these have a direct effect on pulp strength properties (Clarke et. al., 2003). Wood traits affect the quality of wood products, which is especially true for tracheid dimensions regarding paper quality. Also more than 90 per cent of the variation in tracheid length is due to differences among trees within family plots (Beaulieu, 2003). Kuzmin et al., (2008) also reported that tracheids of earlywood and latewood can represent the traits of wood quality identification among intraspecific taxons of Scots pine. Tracheids of latewood show a high sensitivity to changes of climate factors and reflect the genotype reaction to weather conditions of vegetation period in the place of trial. They are especially connected with the relation of water quantity in the first and second half of the vegetation period.

Rathgeber et al. (2006) studied on *Pseudotsuga menziesii* (Douglas fir) in Amance forest near Nancy, France and concluded that radial and tangential tracheid diameters decline from earlywood to latewood by 50 and 15 per cent, respectively. At the same time, radial and tangential cell wall thicknesses increase by 110 and 132 per cent, respectively.

Oluwadare (2007) conducted extensive studies on wood properties Caribbean pine (*Pinus caribaea* Morelet) grown in Afaka, Nigeria. They found that tracheid length increased with increasing age from 2.34 mm in age class 5 to 4.23 mm in age class 25. With the exception of cell wall thickness, other tracheid parameters intersparsely increased with age. Age class 15 seems to be a transition age between the juvenile phase and mature phase. It is only in this trait that within-class variation generally decreases with age from 0.8 per cent in age class 5 to 1.4 per cent in age class 25.

A study on the effect of slope direction on wood quality of *Pinus sylvestris* plantation was done by Li et al., (2002). Results showed that slope direction had a significant effect on the anatomical and physico-mechanical properties. Significant differences were also found in tracheid length, tracheid diameter and tracheid length: width ratio.

Paraskevopoulou (2001) studied horizontal variation of tracheid length in 14 coniferous species of Greece. In this research, it was proven that the age of the tree is the most important factor which affects the radial variation of the tracheid length and explained 66 per cent to 99 per cent of the radial variation in all the studied species. The effect of age is more important in the first years of the age of the tree than later when the trees are mature and the changes in tracheid length are smaller. The age at which the maximum tracheid length is succeeded varies between different species.

A study by Borja et al., 2001 on technological characteristics of the wood of *Pinus caribaea* var. hondurensis found that length, cell wall width and total diameter of the tracheids increases with the distance from the pith to the bark at the three stem heights. The tracheids are longer in any particular ring from the pith at the highest part of the stem and reduce their length towards the base of the tree. In contrast, the diameter of the lumen has an inverse relationship in regard to the distance from the pith.

Dong and Woong (1997), studied cambial development and tracheid length of dwarf pines (*Pinus densiflora* and *P. thunbergii*) and reported that the radial diameter and the number of tracheids in radial rows per annual ring from pith to peripheral region was wider and higher in normal trees than in dwarf trees. Tracheid length was also found to be greater in normal trees than in dwarf trees.

2.2.2.3 Variation in tracheid morphology of softwoods with age

Length on age variation in tracheids of softwoods and fibres of hardwoods has been of considerable interest ever since Sanio's (1872) classical study of tracheid length of Scotch pine (*Pinus silvcstris*). The period over which tracheid length increases rapidly is one of the criteria for the definition of juvenile wood and is associated with a number of undesirable wood properties (Brazier, 1985; Fukazawa and Ohtani, 1982; Panshin and De Zeeuw, 1980). It is reported that the age of trees affects the average values for the strength of the timber and the fibre length (Wormald, 1975). Dinwoodie (1961) comprehensively reviewed the older literature, which contains a number of conflicting reports as to whether cell length remains constant after this steep increase or whether there is further variation.

The combination of age and elevation provided a stronger influence on pulp strength properties accounting for at least 50 per cent of the variation in tensile, tearing strength and stretch. It is reported that tearing strength increases with age but decreases with elevation (Clarke et al., 2003). Pulp yield was influenced most by species and age (39.3 per cent of the variance).

Tracheid length increases from pith to bark in a linear or quadratic fashion within a tree varying from about 2 mm length near the pith to about 6 mm at 14 to 20 years old and, thereafter, decreasing slowly or remaining level (Plumptre, 1984). In young plantation grown material there is an apparent maximum tracheid length occurring between 10 and 20 years depending on the species. This conclusion was based on studies of material with 400-500 years as a maximum age (Bailey, 1958; Bailey and Faull, 1934; Gerry, 1916). Panshin and de Zeeuw (1980) recognized three general types of length-on-age curves for fibres and tracheids; (1) Level curves in which length stays constant after the juvenile phase; (2) Curves showing continuous increase in cell length from the juvenile zone outward; (3) Parabolic curves showing cell length increasing to a maximum followed by a decrease in cell length. These categories are from examples of trees varying in age between 60 and 140 years.

2.2.3 Wood chemical properties

Cellulose accounts for about 42 per cent of the dry matter in softwoods, with the non-crystalline hemicelluloses, lignin and extractives (resins and gums) accounting for the balance. The importance of chemical composition and its influence in wood mechanical properties was emphasized by Heldebrandt (1960). Scurfield et al. (1974) reported that variability resulting from difference in extractives or chemical composition influences wood density and causes great differences in utility of wood.

Paper strength also depends on the lignin and cellulose content of raw plant materials; pulp mechanical strength and especially tensile strength is directly proportional to cellulose content (Madakadze et al., 1999), whereas lignin is an undesirable polymer and its removal during pulping requires high amounts of energy and chemicals.

2.2.3.1 Cellulose content of softwoods

In plants, cellulose is one of the many important polymers and is made up of repeat units of the monomer glucose. Cellulose is a major industrial biopolymer in the forest products, textile, and chemical industries. It also forms a large portion of the biomass useful in the generation of energy. Moreover, cellulose-based biomass is a renewable energy source that can be used for the generation of ethanol as a fuel. Cellulose is synthesized by a variety of living organisms such as plants and algae. It is the major component of plant cell walls with secondary cell walls having a much higher content of cellulose (Tang et al., 2005).

The potential for multiple use of *Pinus caribaea* wood with emphasis on pulp production was assessed by Silva et al. (2004). The materials investigated in this research were wood from 8 year old trees, slabs, peeler core, and the upper part of 23 year old trees. These materials were characterized in terms of basic density, chemical composition, tracheid dimensions, kraft pulping efficiency, and pulp resistance.

Effects of artificial pruning on basic density, chemical composition and tracheid characteristics of *Pinus caribaea* was analysed by Moura and Brito (2001). No differences were observed in wood chemical composition related to artificial pruning in different levels of trunk height. Analysis showed a tendency for wood density increase as pruning intensity increased. A high correlation between the amount of tracheids viewed transversally and wood density was noticed in this study.

The chemical composition of *Pinus oocarpa* wood cultivated in the Brazilian cerrado was estimated by Morais et al. (2005). Chemical analysis and quantification of macromolecular components and volatile extractives was done. The obtained results were: α-cellulose (59.05 %), hemicelluloses A and B (21.22 %), lignin (25.18 %), dichloromethane extractives (2.78 %), ethanol: toluene extractives (4.38 %), hot water extractives (4.31 %) and ash (1.26 %). The cellulose content was high. This result opens perspectives for using *Pinus oocarpa* wood in pulp and paper industries.

Mandre and Korsjukov (2007) estimated the quality of stemwood of *Pinus sylvestris* in an alkalised environment. In this study, concentration of plant nutrients, lignin, cellulose and hemicellulose in the stemwood of 80-85 year-old *Pinus sylvestris* were investigated at different distances from the emission source. It was found that lignin content in stemwood increased, hemicellulose decreased, while cellulose did not change.

The influence of soil attributes on quality of *Pinus taeda* wood for cellulose kraft production was studied by Rigatto et al. (2004). In this study, tree samples were analysed for characters like basic density, chemical composition, tracheid morphological characteristics, nutritional status and kraft cellulose production.

Like wise, a work on genetic variation and genotype by environment interactions of juvenile wood chemical properties in *Pinus taeda* was carried out by Sykes et al. (2006). The study indicated that transition wood had higher α-cellulose content, longer fibre and higher coarseness, but lower lignin than juvenile wood. Dinulica and Leandru (2006) worked on the geographic variability of the fir (*Abies alba*) wood quality and analysed wood quality of standing fir using various parameters like cellulose content, medium width of annual rings, wood density, tracheid length and stem forking. The cellulose content showed an increase with wood density.

Changes in the physical and chemical properties of six softwoods caused by lengthy smoke-heating treatment were reported by Ishiguri et al. (2005). After smoke heating, wood quality, including moisture content, amounts of chemical components, relative degree of crystallinity (RDC) of cellulose, and sapwood colour were examined. No difference was found in the amounts of chemical components between the control woods and the woods that were smoke-heated.

Fang et al. (1995) studied biomass production and pulpmaking performance of a *Metasequoia glyptostroboides* plantation. Biomass production and wood quality were measured from 1990 to 1993. The average cellulose content was 47.5 per cent and the average fibre length was 3.175 mm. The relation between stand age, tree height and cellulose content and fibre length were discussed.

Yeh et al. (2005) rapidly screened wood chemical component variations using transmittance near-infrared spectroscopy. A rapid transmittance near-infrared (NIR) spectroscopy method was used to predict the variation in chemical composition of solid wood. The effect of sample preparation, sample quantity and NIR acquisition time on the quantification of alpha-cellulose and lignin content was investigated. Strong correlations were obtained between laboratory wet chemistry values and the NIR predicted values.

Microanalytical method for the characterization of fiber components and morphology of woody plants were done by Yokoyama et al. (2002). These techniques consist of extractives removal, holocellulose preparation, alpha-cellulose and lignin content determination, and fibre length and coarseness analyses. Fibre morphology and alpha-cellulose content was determined from holocellulose prepared from only 100 mg of wood. Through the development of these microanalytical methods, it is possible to accurately and rapidly analyze fibre morphology and chemical components in a large number of increment core samples.

Estimation of wood density and chemical composition of Sitka spruce (*Picea sitchensis*) and Scots pine (*Pinus sylvestris*) by means of diffuse reflectance mid-infrared Fourier Transform Spectroscopy (FTS) was carried out by Nuopponen et al. (2006). Calibrations for density, lignin, and cellulose were established for all wood species combined into one data set as well as for the separate Sitka spruce data set. MIR spectral data indicated that low-density samples had somewhat higher lignin contents than high-density samples. Correspondingly, high-density samples contained slightly more polysaccharides than low-density samples.

Zhang et al. (2002) reported the effect of chemical composition of slash pine for pulpwood on planting density. The chemical composition of wood samples of 10-year old *Pinus elliottii* from Hunan Province, China was statistically analysed, and a comprehensive investigation on planting density was conducted. Results showed that the content of holocellulose among planting density vary from 73.78-75.56 per cent and planting density showed no significant effect on the contents of holocellulose.

A study on chemical composition and bioavailability of thermally altered *Pinus resinosa* wood was carried out by Baldock and Smernik (2002). Chemical compositions of the chars were assessed by elemental analysis, solid-state ^{13}C nuclear magnetic resonance spectroscopy and diffuse reflectance infrared Fourier transform spectroscopy. The data indicated that the changes in the chemical composition with increasing heating temperature included the chemical changes associated with thermal treatment of cellulose, the major component of wood.

Palmer et al. (1982; 1984) reported that alpha-cellulose rise with age in pine species. According to the rating system designated by Nieschlag et al. (1960), plant materials with 34 per cent and over α-cellulose content were characterized as promising for pulp and paper manufacture from a chemical composition point of view.

2.2.3.2 Lignin content of softwoods

Differences in lignin distribution between earlywood and latewood have been reported (Boutelje, 1972; Fergus et al., 1969; Saka et al., 1982; Wood and Goring, 1971). Donaldson (1985) found that latewood tracheids may have lightly lower middle lamella lignin concentrations than earlywood tracheids of the same growth ring. This trend was observed in three of the five trees examined.

Barnes et al. (1999) determined the effects of rotation age and site altitude on the quality of unbleached kraft pulp made from *Pinus elliotti* and *Pinus patula* grown in the Usutu forest, Swaziland. Wood density, alpha-cellulose, lignin content and ethanol benzene soluble extractives were measured in the wood and tear and tensile indices on the pulp was found.

The response of wood properties, in Scots pine (*Pinus sylvestris*), to elevated temperature and growth were investigated by Kilpelainen et al. (2005). He studied growth and wood properties of 20 year old trees.

Chemical wood properties analysed included concentration of acetone soluble extractives, lignin, cellulose and hemicelluloses. He found out that the chemical composition of wood was affected by elevated carbon dioxide concentration.

A comparative study on the chemical composition of heat treated and gamma irradiated *Pinus sylvestris* wood was carried out by Kasprzyk and Wichacz (2003). The study aimed at determining the chemical composition of heat treated and gamma irradiated pine wood. Chemical analyses of the contents of cellulose, lignin, pentosans and extractives were made. They reported that the cellulose was more sensitive both to gamma irradiation and temperature than lignin.

Xu et al. (2002) analysed the effect of thinning intensities on wood properties of exotic slash pine plantation. Four levels of thinning were carried out in a 10 year old stand of slash pine (*Pinus elliottii*) in China. The different thinning intensities had no significant effect on wood chemical composition (extractives, cellulose, pentosan, lignin and holocellulose). It was concluded that thinning at 50 per cent is the most suitable thinning intensity for growing slash pine for construction timber..

By going through these reviews we can observe that there are numerous studies in other pine species relating wood and/or tracheid properties to the factors of age, species, site and to eventual end use products (Wright et al., 1990; van Buijtenen, 1987; Palmer, 1985; Kibblewhite 1980; Einspahr et at. 1969; van Buijtenen et al., 1961). Most of these works were carried out in Central and South American countries like Brazil, Mexico, Nicaragua Cuba etc. and some studies in African countries like Swaziland, South Africa, Nigeria etc. In the Indian context, only limited amount of works were conducted on tropical pines related to the anatomical and chemical properties. Hence, there is a pertinent need to undertake more research works in the above lines.

Materials and Methods

3. MATERIALS AND METHODS

3.1. MATERIAL

The present investigation was carried out to find the variation in wood anatomical properties of three tropical pine species; viz. *Pinus caribaea* Morelet, *Pinus patula* Schl. et Cham. and *Pinus oocarpa* Schiede, grown in research trials of the Kerala Forest Department in the high ranges of Idukki district, Kerala. The project was carried out in the department of Wood Science, College of Forestry, Kerala Agricultural University during 2008-2010.

3.1.1 Experimental site

The study material was collected from Peerumedu research range of Idukki District, Kerala. Peerumedu is a hill station, located at an altitude of 914 m above sea level (Fig. 2). The climate is equitable, ranging from 32^0 C in March to 16^0 C in December with an average annual rainfall of about 3760 mm. Peerumedu receives a rainfall of about 200 days in an year. The study area experiences a cool climate throughout the year.

The study areas selected in the Peerumedu research range were located at Kolahalamedu, Thotttapara, Vilanjankanam and Thattathikkanam. Details of the locations of tropical pines selected for the study from Peerumedu research range are given in Table 1.

3.2 METHODOLOGY

3.2.1 Selection of trees

Three trees, which were defect free, from each plot for each species were selected at random for collecting wood samples for further detailed investigation. A total of 54 individual trees were selected for collection of samples.

Fig 2. Map showing the study area

Table 1. Details of sampling locations at Peerumade research range, Idukki

Sl. No.	Name of Plantation (Plot)	Area (ha)	Year of planting	Age (Years)	Species selected
1	Pinus Research Garden, Thottapara	0.65	1975	35	*P.caribaea*, *P.patula* and *P.oocarpa*
2	1977-78 Research Garden, Vilanjakanam	2.63	1978	32	*P.caribaea*, *P.patula* and *P.oocarpa*
3	Pinatum, Thottapara	2.50	1979	31	*P.caribaea*, *P.patula* and *P.oocarpa*
4	Pinus Research Garden, Vilanjakanam	0.70	1982	28	*P.caribaea*,*P.patula* and *P.oocarpa*
5	Pinus Research Garden, Vilanjakanam	2.70	1983	27	*P.patula* and *P.oocarpa*
6	Pinus Research Garden, Vilanjakanam	0.90	1984	26	*P.caribaea* and *P.oocarpa*
7	Tropical pine plantation, Thattathikanam	7.60	1985	25	*P.oocarpa*
8	1986 pine plantation, Kolahalamedu	50.80	1986	24	*P. caribaea*

3.2.2 Sample collection

Non-destructive method of sample collection was adopted. For this wood samples were taken using an increment borer (Haglof increment borer CO1512; 800 mm/32", 12/0,500" core diameter, 2-thread) from the selected trees at breast height (Plate 1). From each tree, one core sample, 12 mm thick, was taken.

Plate 1. Collection of increment core samples of wood using Haglof increment borer CO1512: (A) Driving in the borer and inserting borer bit, (B and C) Core samples collected, (D and E) Core samples packed to prevent moisture loss

3.2.3 Preparation of samples

The core samples were further converted to smaller specimens for undertaking studies on wood physical, chemical and anatomical properties.

3.2.3.1 *Wood specific gravity*

From the increment core sample collected using increment borer, 2.5 cm long sections were collected representing three radial positions viz., pith, middle and periphery (Plate 2). Care was taken to see that the bark portion and the core region beyond the pith were discarded. The samples thus collected were used for determining specific gravity.

3.2.3.2 Wood anatomical properties

Increment core samples of wood representing pith, middle and periphery were cut into blocks of size 1.0 cm^3. A total of three blocks representing three regions of wood from each tree were used for detailed investigation of anatomical properties.

3.2.3.3 Wood chemical properties

Core samples obtained from the 1975 Thottapara pine plantation (35 years old) were used to estimate cellulose and lignin content after converting them into fine powder by ball milling for 10-12 minutes. About 2.0 g powder was prepared from each sample.

3.2.4 Estimation of wood properties

3.2.4.1 Wood specific gravity

Wood specific gravity of the pine species was determined using a specific gravity module attached to a precision electronic balance (Schimadzu AUY 220; Plate 3). The converted core samples, from each tree, representing pith, middle

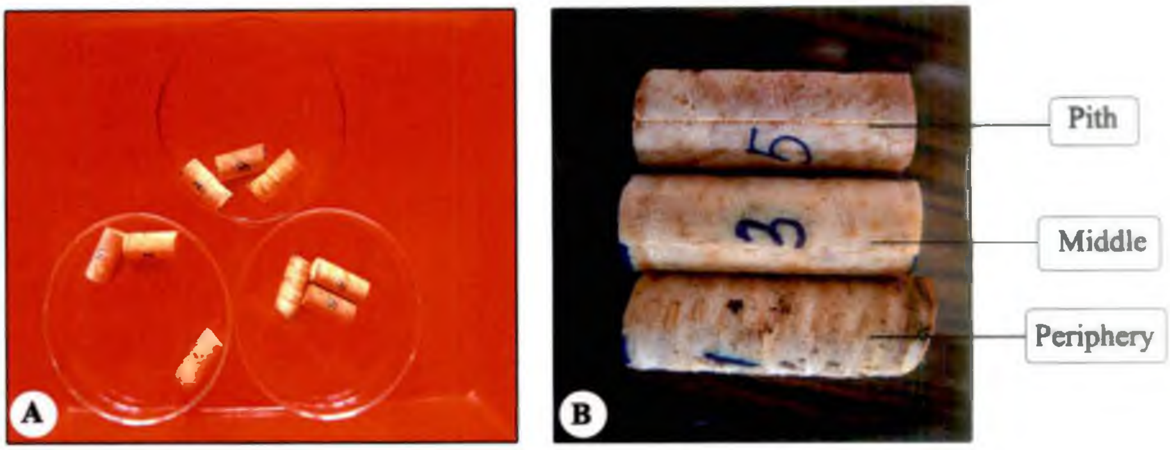

Plate 2A and B. Wood samples used for specific gravity estimation

Plate 3. Specific gravity module attached to electronic balance (Schimadzu AUY 220)

Plate 4. Sliding wood microtome (Leica SM 2000 R) used for wood sectioning

and periphery were used. The specific gravity measurements were estimated on fresh weight, air dry and oven dry basis.

To obtain fresh weight specific gravity, the samples were measured immediately after conversion, using the specific gravity module. Similar observations were repeated in the wood samples when they attained moisture percentage level of 12 to 15 % (equilibrium moisture condition) to obtain air dry specific gravity, whereas oven dry specific gravity was measured after drying the wood samples in an oven, set at an approximately constant temperature of 102°C ±1°C, for such a time as is needed to make its weight constant.

3.2.4.2 Anatomical properties

3.2.4.2.1 Microtomy

Wood specimens of size 1.0 cm^3, representing three radial positions viz., middle, pith and periphery were made out from the samples used for anatomical studies. The specimens were then softened by keeping in water bath (Rotex water bath) at 80^0C for 10-15 minutes. Cross and tangential sections of 10-15 µm thickness were prepared using a Leica sliding microtome (Leica SM 2000 R; Plate 4).

3.2.4.2.2 Maceration

Maceration of the wood samples was done using Jeffrey's method (Sass, 1971). For maceration, Jeffrey's solution was used and it is prepared by mixing equal volumes of 10 per cent potassium dichromate and 10 per cent nitric acid.

Radial chips of wood shavings were taken from the 1 cm^3 wood blocks separately from the three radial positions viz., pith, middle and periphery. These chips were boiled in the maceration fluid for 15-20 minutes so that the individual fibres were separated. 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 saffranin and mounted on temporary slides using glycerin as the mountant.

3.2.4.2.3 Staining procedure

Permanent slides of transverse and tangential sections were stained using the procedure outlined by Johansen (1940). In this, 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. They were subsequently dipped in acetone followed by xylene and finally mounted in DPX mountant to prepare the permanent slides.

3.2.4.2.4 Image Analysis

Microscopic examination and quantification of sections was undertaken using an Image Analyzer (Labomed-Digi 2; Plate 5). It consists of a microscope, digital camera and PC (Personal computer). The image analyzer provides quick and accurate data replacing the more laborious traditional methods. The digital camera provides digitized images which are analyzed by the computer software (Labomed DigiPro-2). The software provides several classes of measurements like length, diameter, area and count.

3.2.4.2.5 Observations

From the macerated tracheids, observations like tracheid length, tracheid diameter, tracheid wall thickness and tracheid lumen diameter for each of the species were measured using the Image Analyzer. Each measurement was repeated five times for all the above characters at each radial position, viz., pith, middle and periphery and is expressed in micrometers (μm).

Tangential longitudinal sections (T.L.S) were used to measure ray height (μm) and ray width (μm), whereas transverse sections (T.S) were used to

Plate 5. Image Anayser (Labomed Digi-2) used for anatomical quantification

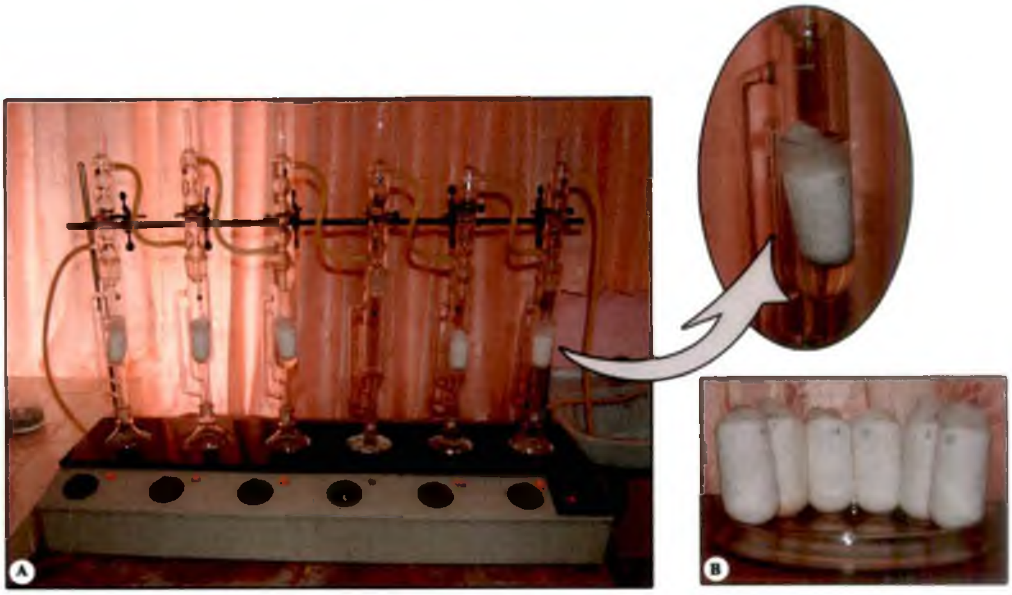

Plate 6. Purification of wood powder and preparation of EXR for estimation of lignin: (A) Soxhlet apparatus used for purification, (B) Extraction thimble (25x70 mm) bunged with cotton wool

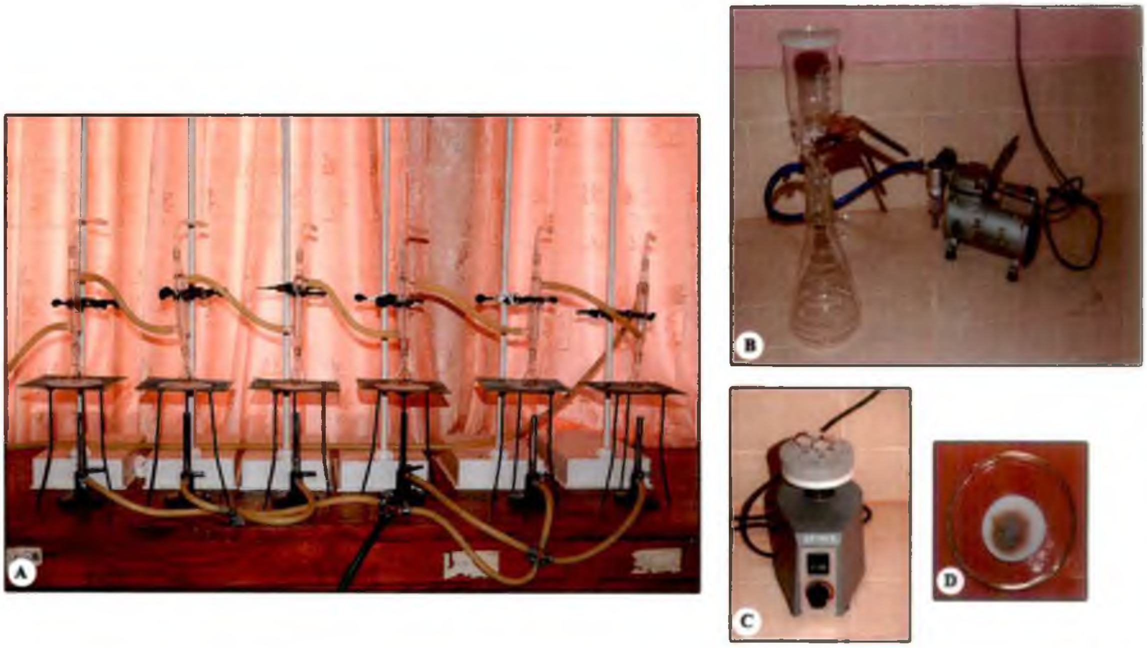

Plate 7. The Microklasson technique of quantification of insoluble lignin: (A) Round bottomed flask assembly, (B) Vacuum filteration system, (C) Vortex mixer used for mixing, (D) Pre-weighed glass microfibre with lignin residue

determine tracheid frequency and tissue proportion in both early wood and late wood region. Tracheid frequency (tracheids per mm^2) was determined by counting the number of tracheids in randomly selected fields of the section with the help of the image analysis software, Labomed-Digi 2 and was expressed as number per millimeter (mm). Tissue proportions like tracheid and ray were determined by counting their number along a line drawn on the image of the transverse section and captured with the aid of the image analyzer. It was then expressed on a percentage basis. Five observations each were taken for all the characters. For each character, observations were taken from all the three radial positions in the transverse sections.

Different criteria which are important in pulp and papermaking were derived from the data obtained using the following equations (Uju and Ucwoxe, 1997; Yáñez-Espinosa et al., 2004):

$$\text{Runkel Ratio} = \frac{2 \times \text{Fibre wall thickness (FWT)}}{\text{Fibre lumen diameter (FLD)}}$$

$$\text{Slenderness Ratio} = \frac{2 \times \text{Fibre Length (FL)}}{\text{Fibre diameter (FD)}}$$

$$\text{Rigidity Coefficient} = \frac{2 \times \text{Fibre Wall Thickness (FWT)}}{\text{Fibre diameter (FD)}}$$

$$\text{Flexibility Coefficient} = \frac{2 \times \text{Fibre Lumen Diameter (FLD)}}{\text{Fibre diameter (FD)}}$$

$$\text{Shape Factor} = \frac{D^2 - L^2}{D^2 + L^2}$$

Where,

D-Fiber width

L-Lumen width

3.2.4.3 Chemical properties

3.2.4.3.1 Estimation of cellulose

Cellulose content of the wood was estimated following Sadasivam and Manikam (1992). For this finely powdered samples were used for the cellulose estimation. In this method, 3.0 ml of acetic/nitric reagent was added to 0.1 g of sample in a test tube and mixed in a vortex mixer. The test tube was placed in a water bath maintained at 100^0 C for 30 minutes. It was cooled and centrifuged (Eppendorf centrifuge 5804 R) at 5000 rpm for 15 minutes. After centrifuging, the supernatant liquid was discarded and the residue was washed with distilled water and to this 10 ml sulphuric acid (67%) was added and kept for one hour. The solution thus obtained was diluted to 100 ml by adding distilled water. From this, 1.0 ml was taken and mixed well with 10 ml anthrone reagent and the test tubes were kept in a water bath at 65^0 C for 10 minutes. A blank was also set with anthrone reagent and distilled water. The solution was cooled and the colour was measured using a spectrophotometer (Thermospectronic-20) at 630 nm.

A standard was prepared using 100 mg cellulose in a test tube. A series of volumes viz., 0.2 ml, 0.4 ml, 0.6 ml, 0.8 ml and 1.0 ml was taken and colour was developed. This was measured using spectrophotometer. From the readings obtained from the standard, a standard graph was drawn and the percentage of cellulose was calculated using the formula,

$$\text{Cellulose (\%)} = \left(\frac{\text{OD of sample}}{\text{OD of standard}}\right) \times \text{Conc. of standard} \times \left(\frac{\text{Total Volume}}{\text{Volume taken}}\right) \times \left(\frac{\text{Volume made up}}{\text{Weight of sample}}\right) \times 100$$

Where, OD is Optical density

3.2.4.3.2 Estimation of lignin

Estimation of insoluble lignin was undertaken using Micro-Klason technique (Whiting et al., 1981)

3.2.4.3.2a Purification of wood powder and preparation of EXR (Extractive free xylem residue)

Soluble sugars, phenolics and extractives from the xylem powder were removed using a soxhlet apparatus. One gram cell wall residue (CWR) was weighed in labelled cellulose thimble (extraction thimble 25x70 mm) and the mouth was bunged with cotton wool. The thimble was kept in soxhlet apparatus and boiled for 30 minutes in distilled water (80 ml). This was extracted in ethyl alcohol for 30 minutes (80 ml) followed by 10 minutes rinsing. The next stage of extraction was carried out using ethyl alcohol and toluene (1:1; 40+40 ml) for 30 minutes followed by 10 minutes rinsing. Final extraction was carried out with acetone (10 ml) for 5 minutes boiling followed by 7 minutes rinsing. The thimble was removed from the soxhlet and kept open for 24 hours. The dried EXR was taken out carefully from the thimble using spatula to a pre weighed and labeled plastic tube and was kept in desiccators for lignin estimation. Purification of wood powder and preparation of EXR is shown in Plate 6.

3.2.4.3.2b Quantification of insoluble lignin (Micro-klasson technique)

The steps involved in the Micro-klasson technique of quantification of insoluble lignin is given in Plate 7. 1-20 mg EXR was weighed in an eppendorf (10-12 mg is sufficient) to which 15 µl H_2SO_4 (72%) per mg of EXR was added. The mixture was vortexed well to ensure that all of the EXR is mixed well in acid. For proper mixing, a glass pipette/needle was used. The mixture was kept for 1.5 hours at 25° C and vortexed every 15 minutes in a shaker. The mixture was transferred to a 10 ml round bottomed flask using sufficient distilled water to dilute the acid from 72 per cent to 3 per cent. This was done by adding 23.28 µl of distilled water per micro liter of H_2SO_4. A micropipette of 1.0 ml was used to schoose the lumps up and down to break them up. The flask was placed over flame of the reflux condenser for 3 hours ensuring that it did not boil too hard or the contents did not stick all around the flask. The flask was swirled occasionally to dislodge solids adhering to sides of the flask. After 3 hours, the content was filtered on to a pre-weighed glass microfibre filter attached to a vacuum filtration system. Then the filter paper was dried in the oven for 4 hours at 40° C (overnight drying is better) and finally the filter was reweighed along with the residue.

The insoluble lignin content was calculated using the formula,

$$\text{Lignin (\%)} = \frac{(Z - Y)}{X} \times 100$$

Where, X-Weight of EXR

Y-Weight of filter paper alone (pre-weighed)

Z-Weight of filter along with residue

The lignin percentage thus obtained is represented as Klasson lignin or insoluble lignin (percentage weight of EXR).

3.2.5 Statistical analysis

The present investigation was an attempt to study the variation in wood properties of three species of tropical pines viz., *P.caribaea, P.patula* and *P.oocarpa.* At each location there were different age groups of species and observations were made at three levels viz., pith, middle and periphery portion of wood at breast height level to find out the radial variation in wood properties. Thus each sample (species) is composed of sub samples (age and position). The sampling and sub sampling gives rise to nested or hierarchical classification (Sokal and Rohlf, 2000). Therefore, in this study, NESTED ANOVA was carried out to find variation that exists between species, age group and positions, using the statistical package, "SAS (ver. 10)".

As the data for all the three species were available for four age levels those data were utilized for finding out the variation between three species, age group and positions. For this, ANOVA was carried out using univariate mixed model with two levels of errors to explain variation in different parameters studied. Variation between trees within age by species is acted as error for comparing the variation due to age, species, and their interaction. All other effects were compared using residual error. Means were compared using least significant difference (LSD) method wherever the F-values were found to be significant.

One-way analysis of variance, followed by LSD, was used to test the significance of cellulose content and lignin content, among species in the Thottapara 1975 pine plantation.

Simple correlation coefficient was computed taking complete set of data to examine the interrelationships between wood properties. Regression analysis was carried out to compute relationship between selected wood variables (dependent variable) and radial positions (independent variable). Interdependence among the wood properties was also computed by this. Different models were tired and the best fitted models were selected based on adjusted R^2.

Results

4. RESULTS

Results pertaining to variation in physical, anatomical and chemical properties of the three selected tropical pine species; viz. *Pinus caribaea* Morelet, *Pinus patula* Schl. et Cham. and *Pinus oocarpa* Schiede, grown in research trials of the Kerala Forest Department in the high ranges of Idukki district, Kerala with special reference to their suitability for pulping are presented under the following categories:

I. Physical properties
  i. Specific gravity
    a. Fresh weight basis
    b. Air dry basis
    c. Oven dry basis
II. Anatomical properties
  A. Tracheid morphology
    i. Tracheid length
    ii. Tracheid diameter
    iii. Tracheid wall thickness
    iv. Tracheid lumen diameter
    v. Runkel ratio
    vi. Shape factor
    vii. Slenderness ratio
    viii. Coefficient of flexibility
    ix. Coefficient of rigidity
  B. Ray morphology
    i. Ray height

        ii. Ray width
    C. Tissue frequency
        i. Tracheid frequency in earlywood
        ii. Tracheid frequency in latewood
    D. Tissue proportions
        i. Tracheid percentage in earlywood
        ii. Ray percentage in earlywood
        iii. Tracheid percentage in latewood
        iv. Ray percentage in latewood
III. Chemical properties
        i. Cellulose content
        ii. Lignin content

NESTED ANOVA was carried out to understand the variation in the above properties in the pine species belonging to four ages viz., 28, 31, 32 and 35 years. Results obtained are presented by taking into account the variations due to age, species and radial position (for those properties for which horizontal variation was studied), and their interaction effects. Mean values of wood properties have also been given for understanding wood property variation due to the above mentioned effects.

The variation in chemical properties of three pine species belonging to 35 year old plantation was found out by carrying out one-way ANOVA and the mean values were presented species wise. Summary of ANOVA carried out are presented in appendices I to XXII.

To find out the relationship between wood properties in the three pine species, regression analysis was carried out for selected characters and results are presented through regression equations. Radial relationships of selected wood properties were also studied through regression equations. The inter-relationship between selected pairs of physical and anatomical properties were also studied through correlation analysis and have been presented separately for each species.

4.1 PHYSICAL PROPERTIES

4.1.1 Specific gravity

4.1.1.1 Specific gravity (fresh)

4.1.1.1a Variation due to age and species

Results of NESTED ANOVA show that the interactions between age and species are significant (1% level). This indicates that the effect of age is varying with species. However, comparison of age means averaged over all species and comparison of species means averaged over all ages are not useful. The more appropriate comparisons are those between age means of the same species or between species means at the same age level. This was done by using LSD comparison and results are presented in Table 2 and Figure 3.

From Table 2, it can be seen that there is no significant variation between species within each age levels. Specific gravity (fresh) was found to range in the 28 years old plantation from 0.723 (*Pinus caribaea*) to 0.897(*Pinus oocarpa*); in the 31 years old plantation it ranged from 0.824 (*Pinus patula*) to 0.950 (*Pinus oocarpa*); in the 32 years old plantation it ranged from 0.799 (*Pinus patula*) to 0.873 (*Pinus caribaea*) and in the 35 years old plantation it ranged from 0.792 (*Pinus patula*) to 0.915 (*Pinus caribaea*) (Fig. 3A).

A comparison shows that significant difference between age group was found only in the case of *Pinus caribaea* (Fig. 3A). Specific gravity at the age of 28 years is comparatively lower (0.723) and it is homogeneous with that of 32 years (0.873) and significantly lower than the other two age levels. The species *Pinus patula* and *Pinus oocarpa* showed no significant variation between age levels. In *Pinus patula*, values were found to range between 0.792 (35 years old plantation) to 0.825 (28 years old plantation). *Pinus oocarpa* had maximum value in 31 years old plantation (0.950) and lowest value in 32 years old plantation (0.828).

Table 2. Mean wood specific gravity (fresh) of tropical pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Specific gravity (fresh)				
Pinus caribaea	0.723$^{a\ B}$ (0.197)	0.935$^{a\ A}$ (0.064)	0.873$^{a\ AB}$ (0.084)	0.915$^{a\ A}$ (0.077)	0.861^{ab} (0.141)
Pinus patula	0.825$^{a\ A}$ (0.115)	0.824$^{a\ A}$ (0.068)	0.799$^{a\ A}$ (0.151)	0.792$^{a\ A}$ (0.186)	0.810^{b} (0.132)
Pinus oocarpa	0.897$^{a\ A}$ (0.084)	0.950$^{a\ A}$ (0.184)	0.828$^{a\ A}$ (0.151)	0.897$^{a\ A}$ (0.129)	0.894^{a} (0.142)
F value	4.97** (for comparing between age and species) 3.36** (for comparing species averaged over all ages)				
C.D	0.187(for comparing between age and species) 0.039 (for comparing species averaged over all ages)				

* Significant at 5 % level; ns - non significant; C.D - critical difference; values within parentheses is standard deviation; means with same small letter as superscript in a column are homogeneous; means with same upper case letters as superscript in a row are homogeneous

Species mean, averaged over all ages was found to differ significantly from each other at 1 per cent level. These results are presented in Table 2 and Figure 3B. From this it can be found out that *Pinus patula* (0.810) differed significantly from *Pinus oocarpa* (0.894), whereas *Pinus caribaea* (0.861) was found to be homogenous with other two species.

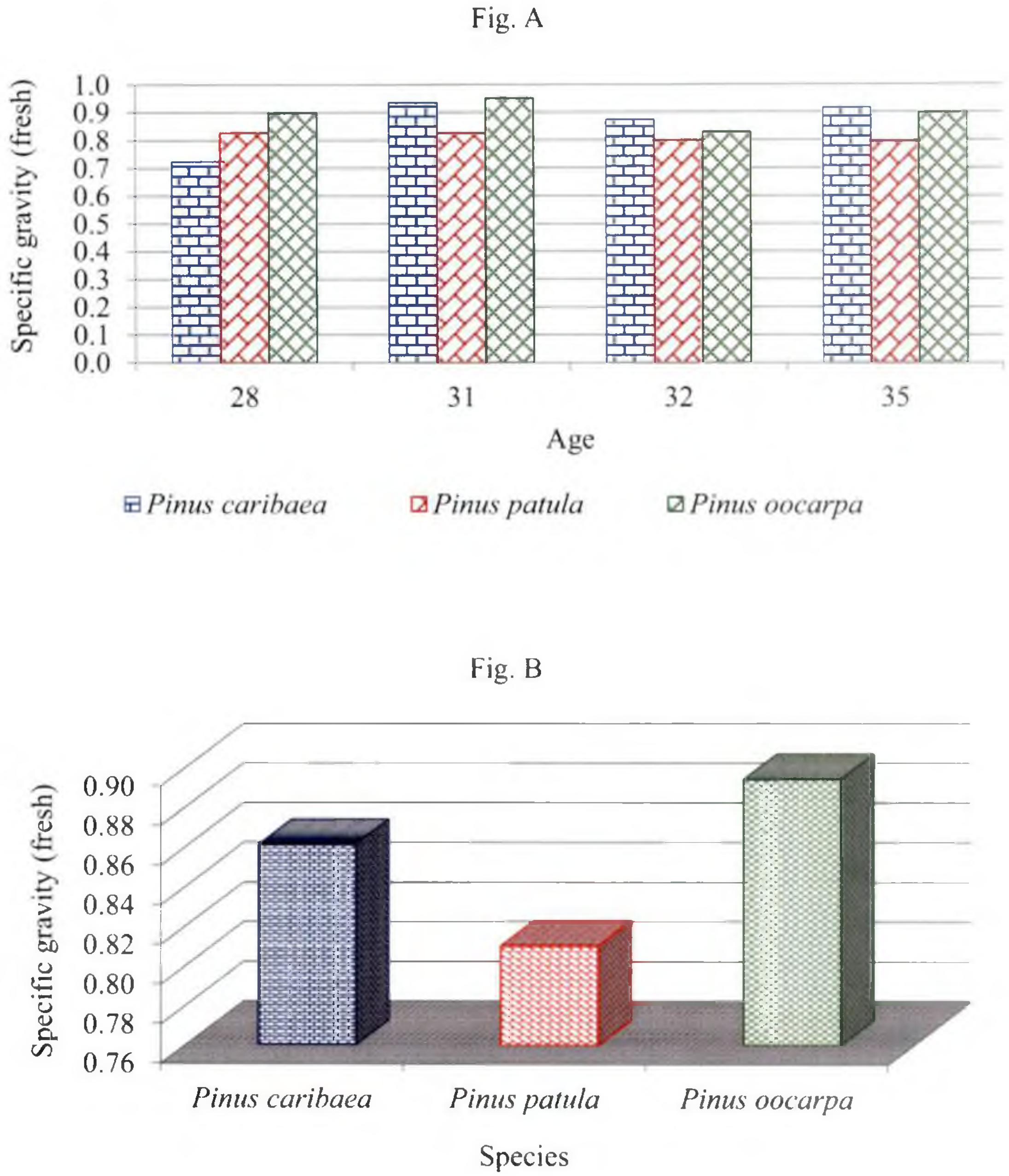

Fig. 3. Variation in specific gravity (fresh) between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

4.1.1.1b Variation due to position in a species within an age group

The interactions between age and position within species were found to be significant (5 % level). Hence, the comparison between positions within each species for each age level was done and the results are given in Table 3 and Figure 4.

In the younger plantation under study (28 years old) there was no significant difference among radial positions in *Pinus oocarpa* with respect to specific gravity (fresh). The value was found to range from 0.851 (pith) to 0.972 (periphery). But *Pinus caribaea* and *Pinus patula* showed significant differences radially. In the case of *Pinus caribaea*, both pith (0.521) and middle (0.705) positions were found to have homogenous values. But these two positions were found to vary significantly from the periphery (0.982). In *Pinus patula* both periphery (0.941) and middle (0.888) values did not differ significantly from each other. On the other hand, the pith position (0.682) had the lowest value and it differed significantly from the other two radial positions (Fig. 4A).

Radially, specific gravity (fresh) showed an increasing trend from pith to periphery position in 31 years old *Pinus patula* (Fig. 4B) i.e. 0.765 at pith and 0.905 at periphery. In *Pinus cariabea* had values that ranged from 0.875 (pith) to 0.944 (middle). Also there was no significant difference between the radial positions in *Pinus cariabaea* and *Pinus patula.* In *Pinus oocarpa*, the pith (0.761) differed significantly from the other two positions (1.033 at middle and 0.949 at periphery), whereas later two positions were found to be homogenous with each other.

From Figure 4C, it can be seen that specific gravity (fresh) was found to increase from pith to periphery position in 32 years old *Pinus patula* and *Pinus oocarpa* viz., 0.647 to 0.865 and 0.651 to 1.054 respectively. In both of these species, the pith differed significantly from the other two radial positions. But in

Table 3. Mean wood specific gravity (fresh) at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Specific gravity (fresh)		
28	*Pinus caribaea*	0.521^{b} (0.119)	0.705^{b} (0.070)	0.982^{a} (0.013)
	Pinus patula	0.682^{b} (0.076)	0.888^{a} (0.036)	0.941^{a} (0.012)
	Pinus oocarpa	0.851^{a} (0.046)	0.870^{a} (0.114)	0.972^{a} (0.056)
31	*Pinus caribaea*	0.875^{a} (0.080)	0.944^{a} (0.021)	0.892^{a} (0.048)
	Pinus patula	0.765^{a} (0.031)	0.842^{a} (0.096)	0.905^{a} (0.049)
	Pinus oocarpa	0.761^{b} (0.234)	1.033^{a} (0.015)	0.949^{a} (0.030)
32	*Pinus caribaea*	0.922^{a} (0.037)	0.805^{a} (0.116)	0.987^{a} (0.006)
	Pinus patula	0.647^{b} (0.082)	0.846^{a} (0.164)	0.865^{a} (0.016)
	Pinus oocarpa	0.651^{b} (0.084)	0.884^{a} (0.099)	1.054^{a} (0.031)
35	*Pinus caribaea*	0.837^{a} (0.069)	0.925^{a} (0.055)	0.943^{a} (0.038)
	Pinus patula	0.585^{b} (0.173)	0.849^{a} (0.077)	0.904^{a} (0.012)
	Pinus oocarpa	0.756^{b} (0.129)	0.964^{a} (0.044)	0.971^{a} (0.019)
F value	2.32* (for comparing between age and position within species)			
C.D	0.184			

* Significant at 5 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

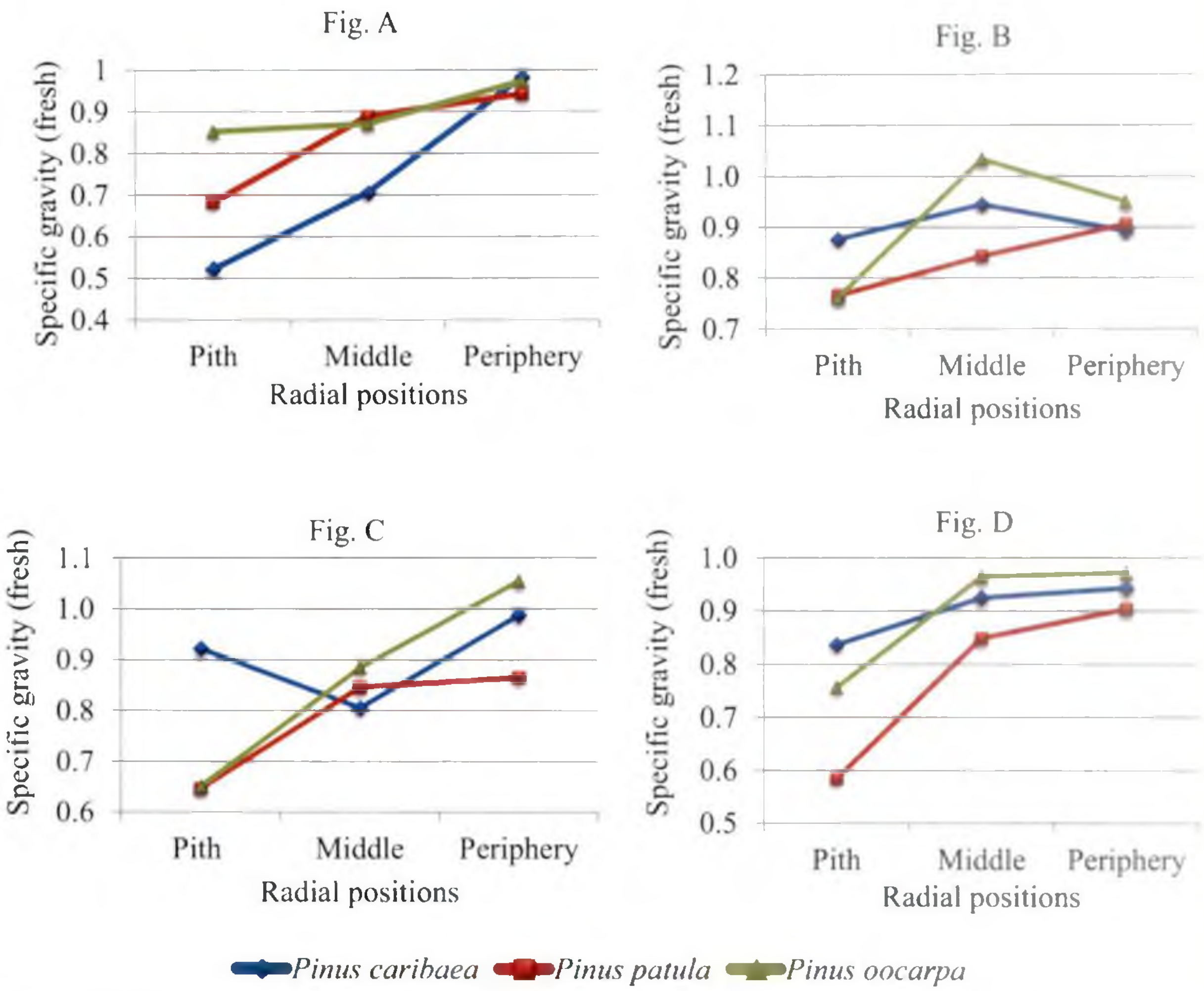

Fig. 4. Radial variation of specific gravity (fresh) in pine species belonging to different ages: (A) 28 years; (B) 31 years;(C) 32 years; (D) 35 years

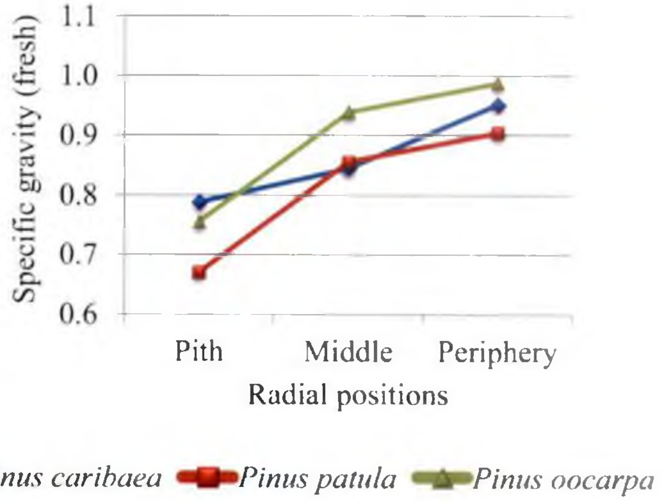

Fig. 5. Radial variation in mean specific gravity (fresh) of pine species averaged over all ages

Pinus caribaea, the values showed no significant difference among radial positions and interestingly the highest value was found to be at the periphery (0.987) compared to middle (0.805) and pith (0.922) positions.

Radial variations of specific gravity (fresh) in the three pines which are 35 years old are presented graphically in Figure 4D. It can be seen that specific gravity (fresh) was found to increase from pith to periphery position in *Pinus caribaea*, *Pinus patula* and *Pinus oocarpa*. In both *Pinus patula* and *Pinus oocarpa*, pith position showed significant difference from the other two radial positions. *Pinus caribaea* showed no difference in radial positions and this ranged from 0.837 at pith to 0.943 at the periphery position. In *Pinus patula*, specific gravity (fresh) was found to be 0.585 at pith, 0.849 at middle and 0.904 at periphery and in *Pinus oocarpa* it varied from 0.756 at pith, 0.964 at middle and 0.971 at periphery.

4.1.1.1c Variation due to position within species averaged across all ages

Specific gravity (fresh) showed highly significant variation with respect to radial positions within each species (1% level). Species mean averaged across all the ages in different radial positions showed an increasing trend from pith to periphery position in all the three species (Table 4 and Fig. 5). But this variation in radial position within the species is also influenced by age (Table 3).

From Table 4 it can be found out that *Pinus caribaea* had an average value of 0.788 at pith, 0.845 at middle and 0.951 at periphery position. The value at the periphery differed significantly from middle and pith positions and the latter two were homogeneous with each other. In *Pinus patula* the periphery (0.904) and middle (0.856) position showed no significant differences. But the pith (0.670) differed significantly from the other two positions. *Pinus oocarpa* also showed significant differences between pith (0.755) and periphery (0.987) positions, while middle (0.938) position was found to be homogenous with both periphery and pith position.

Table 4. Mean wood specific gravity (fresh) of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Specific gravity (fresh)		
Pith	0.788^{b} (0.179)	0.670^{b} (0.112)	0.755^{b} (0.142)
Middle	0.845^{b} (0.119)	0.856^{a} (0.091)	0.938^{ab} (0.096)
Periphery	0.951^{a} (0.048)	0.904^{a} (0.036)	0.987^{a} (0.052)
F value	20.65** (for comparing between position within a species)		
C.D	0.092		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.1.1.2 Specific gravity (air dry)

4.1.1.2a Variation due to age and species

The data on variation in specific gravity (air dry) with respect to age and species is presented in table 5 and Figure 6. Analysis of variance revealed that age and species interactions were not significant. Hence, the effect of age is not varying with species with in an age and between different ages within a species.

The specific gravity (air dry) among species was found to range in the 35 years old plantation from 0.554 (*Pinus caribaea*) to 0.747 (*Pinus oocarpa*). In the 32 year old plantation it ranged from 0.629 (*Pinus oocarpa*) to 0.660 (*Pinus caribaea*), in the 31 years old plantation it ranged from 0.569 (*Pinus caribaea*) to 0.659

(*Pinus oocarpa*) and in 28 years old plantation it ranged from 0.534 (*Pinus caribaea*) to 0.681 (*Pinus oocarpa*). These variations among species in different ages is presented in Table 5 and graphically illustrated in Figure 6A.

Table 5. Mean wood specific gravity (air dry) of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Specific gravity (air dry)				
Pinus caribaea	0.534 (0.132)	0.569 (0.135)	0.660 (0.133)	0.554 (0.175)	0.579^{b} (0.147)
Pinus patula	0.614 (0.151)	0.596 (0.156)	0.643 (0.206)	0.593 (0.219)	0.612^{ab} (0.178)
Pinus oocarpa	0.681 (0.102)	0.659 (0.102)	0.629 (0.093)	0.747 (0.108)	0.679^{a} (0.106)
F value	1.29^{ns} (for comparing between age and species) 5.11* (for comparing species averaged over all ages)				
C.D	0.114 (for comparing species averaged over all ages)				

* Significant at 5 % level; ns - non significant; C.D - critical difference; values within parentheses is standard deviation; means with same small letter as superscript in a column are homogeneous

From Table 5 and Figure 6A it can be seen that the specific gravity (air dry) was found to vary in *Pinus caribaea* from 0.534 (28 years old plantation) to 0.660 (32 years old plantation), in *Pinus patula* it ranged from 0.593 (35 years old plantation) to 0.643 (32 years old plantation) and in *Pinus oocarpa* it was found to range from 0.629 (32 years old plantation) to 0.747 (35 years old plantation).

Species mean, averaged over all ages was found to differ significantly from each other at 5 per cent level. These results are presented in Table 5 and Figure 6B. From this it can be found out that *Pinus caribaea* (0.579) differed significantly from *Pinus oocarpa* (0.679) and not with *Pinus patula* (0.612). On the other hand,

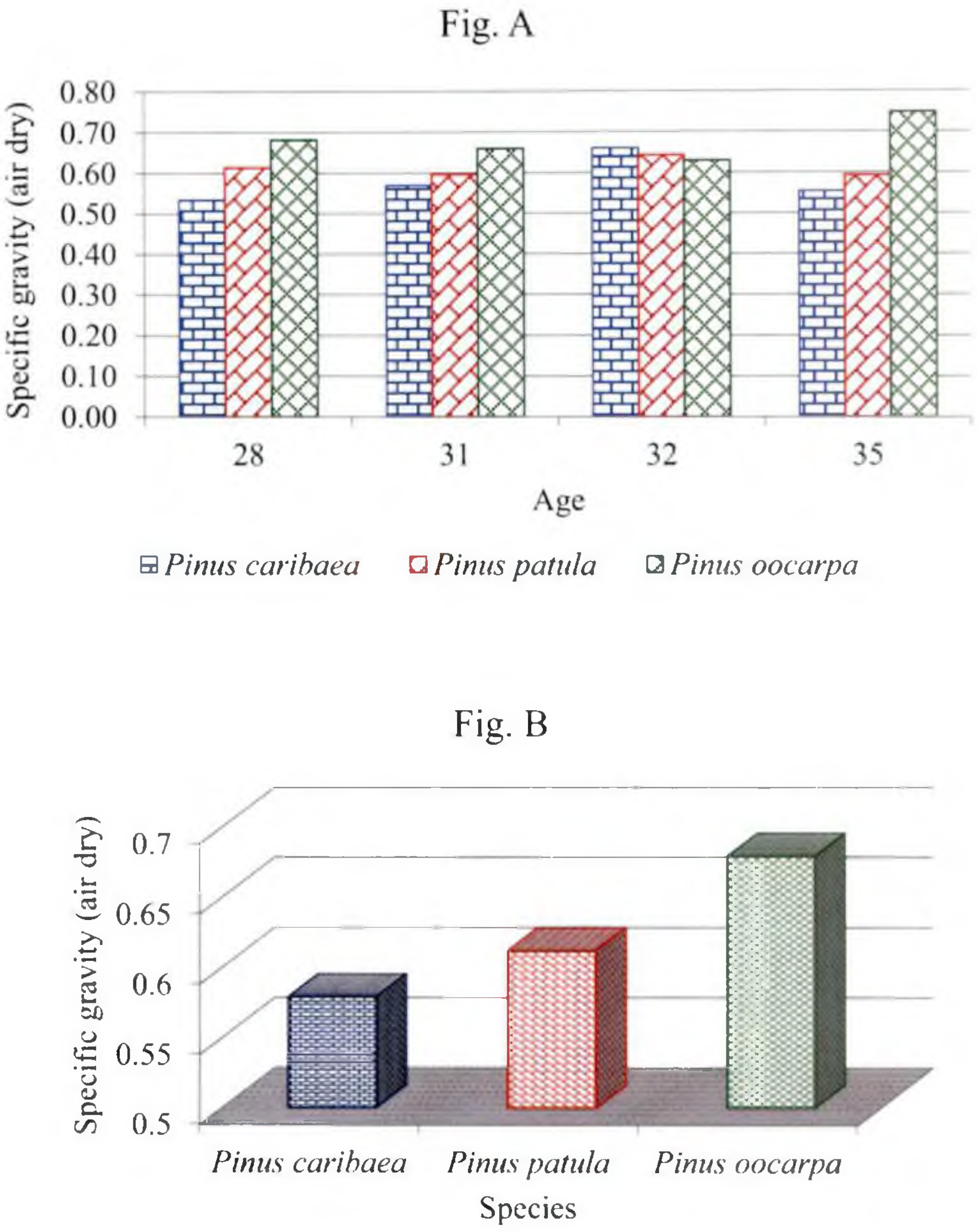

Fig. 6. Variation in specific gravity (air dry) between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

Pinus oocarpa and *Pinus patula* showed no significant variation in specific gravity (air dry) (Table 5).

4.1.1.2b Variation due to position in a species within an age group

Analysis of variance showed that there is no significant difference in specific gravity (air dry) due to the interactions between age and position within species. The summarized results are presented in Table 6 and Figure 7.

The values showed an increasing trend in *Pinus caribaea* from pith (0.449) to periphery position (0.676) in 28 years old plantation (Fig. 7A). But in *Pinus patula* it first increased from pith (0.445) to middle position (0.730) and then decreased in the periphery position (0.666). While in *Pinus oocarpa*, it first decreased from pith (0.680) to middle (0.652) and then increased in the periphery position (0.711).

From Figure 7B it can be seen that the specific gravity values (air dry) of 31 years old plantation was found to increase from pith to periphery position in *Pinus patula* and *Pinus oocarpa* i.e. 0.501 to 0.708 and 0.546 to 0.767 respectively. But in *Pinus caribaea* the value was found to decrease from pith (0.560) to middle (0.489) and finally increase to the periphery position (0.659).

In the 32 years old plantation the specific gravity (air dry) values in *Pinus patula* and *Pinus oocarpa* was found to increase from pith to periphery position viz., 0.440 to 0.816 and 0.547 to 0.689 respectively (Fig. 7C). On the other hand, in *Pinus caribaea* the values were found to first decrease from pith (0.716) to middle (0.603) and then it increased to the periphery position (0.661).

The variation in specific gravity (air dry) is found to increase in all the three pine species from pith to periphery position in 35 years old plantation (Fig. 7D). *Pinus caribaea* was found to have values ranging from 0.436 (pith) to 0.697 (periphery). The values ranged from 0.367 (pith) to 0.836 (periphery) in

Table 6. Mean wood specific gravity (air dry) at pith, middle and periphery of pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Specific gravity (air dry)		
28	*Pinus caribaea*	0.449 (0.128)	0.478 (0.078)	0.676 (0.038)
	Pinus patula	0.445 (0.04)	0.730 (0.066)	0.666 (0.137)
	Pinus oocarpa	0.680 (0.192)	0.652 (0.037)	0.711 (0.032)
31	*Pinus caribaea*	0.560 (0.21)	0.489 (0.061)	0.659 (0.055)
	Pinus patula	0.501 (0.202)	0.580 (0.148)	0.708 (0.039)
	Pinus oocarpa	0.546 (0.014)	0.666 (0.059)	0.767 (0.038)
32	*Pinus caribaea*	0.716 (0.226)	0.603 (0.088)	0.661 (0.046)
	Pinus patula	0.440 (0.056)	0.673 (0.217)	0.816 (0.108)
	Pinus oocarpa	0.547 (0.098)	0.650 (0.091)	0.689 (0.011)
35	*Pinus caribaea*	0.436 (0.027)	0.528 (0.202)	0.697 (0.169)
	Pinus patula	0.367 (0.034)	0.578 (0.151)	0.836 (0.046)
	Pinus oocarpa	0.625 (0.043)	0.797 (0.05)	0.820 (0.091)
F value	1.51^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

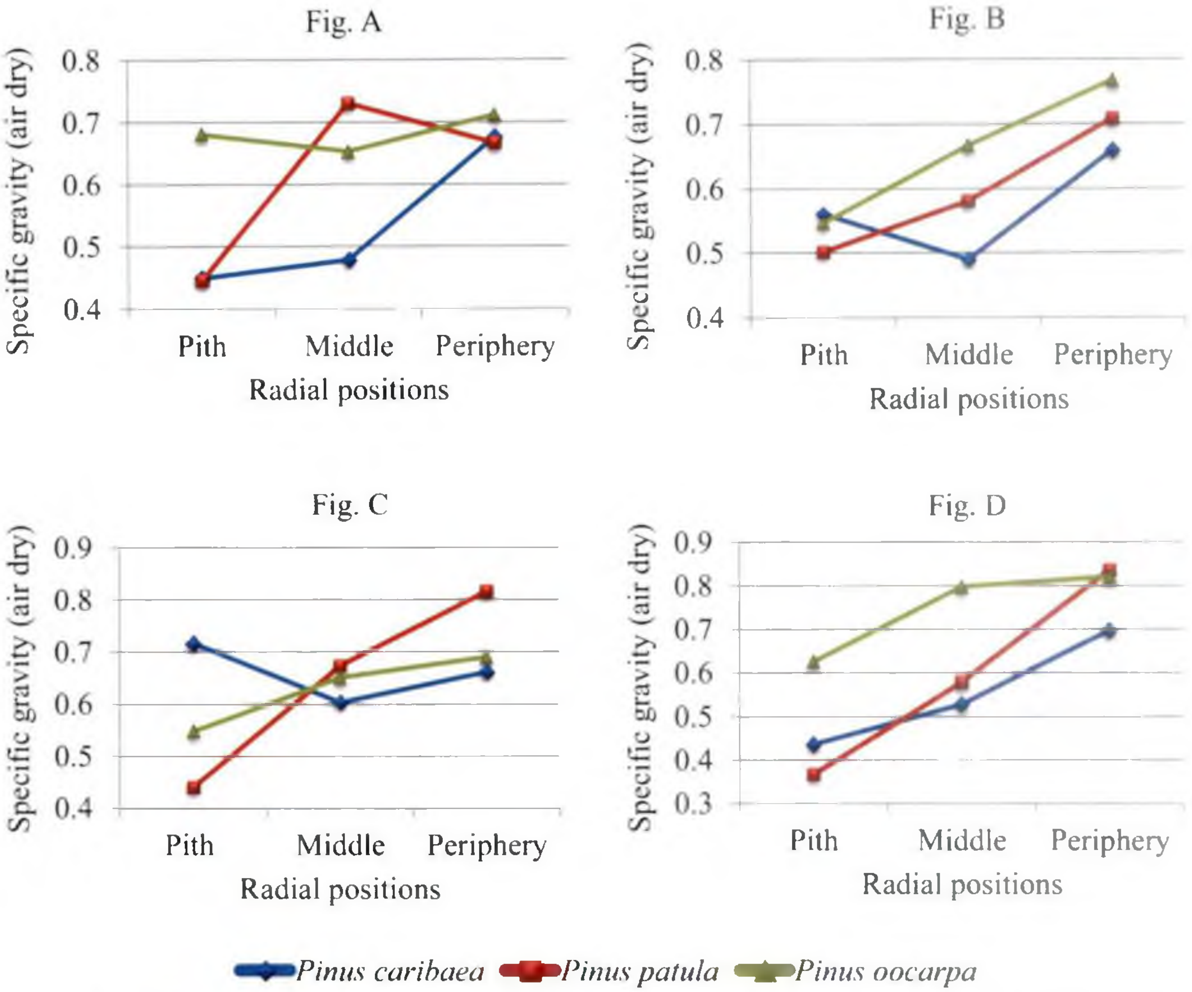

Fig. 7. Radial variation of specific gravity (air dry) in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

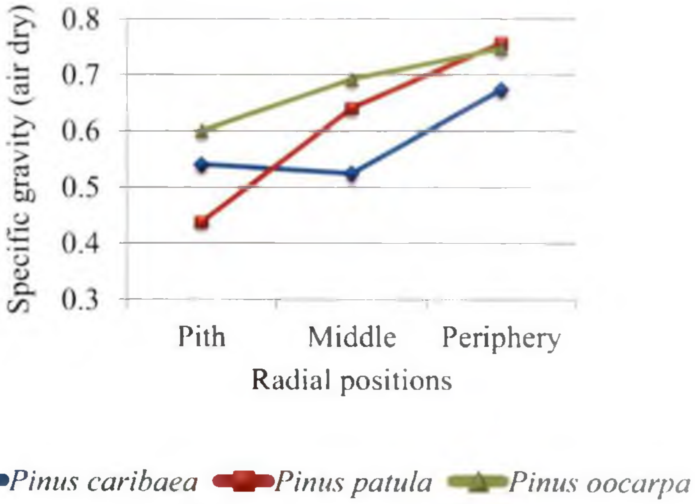

Fig. 8. Radial variation in mean specific gravity (air dry) of pine species averaged over all ages

Pinus patula. It can also be seen that *Pinus oocarpa* had values ranging from 0.625 (pith) to 0.820 (periphery).

4.1.1.2c Variation due to position within species averaged across all ages

The summarized data on variation of specific gravity (air dry) in radial positions of three species across all ages are presented in Table 7 and graphically shown in Figure 8. Variation between species is highly significant at 1 per cent level and age did not have any influence on this variation (Table 6)

Table 7. Mean wood specific gravity (air dry) of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Specific gravity (air dry)		
Pith	0.540^{b} (0.185)	0.438^{c} (0.105)	0.600^{b} (0.111)
Middle	0.524^{b} (0.115)	0.640^{b} (0.148)	0.691^{ab} (0.083)
Periphery	0.673^{a} (0.082)	0.757^{a} (0.108)	0.747^{a} (0.069)
F value	15.34** (for comparing between position within a species)		
C.D	0.109		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

There is an increasing trend in values from pith to periphery position in *Pinus patula* and *Pinus oocarpa*, whereas in *Pinus caribaea* it showed a decrease in value from pith to middle and then increased at periphery position. In *Pinus caribea*, the pith (0.540) and middle (0.524) position was found to be homogenous and both these differed significantly from the periphery (0.673) position. But in *Pinus patula* the three radial positions differed significantly from each other i.e. 0.438 in the pith, 0.640 in the middle and 0.757 in the periphery position. In *Pinus oocarpa* there is significant difference between pith (0.600) and periphery position (0.747). But these two positions were found to have no significant difference with middle position (0.691).

4.1.1.3 Specific gravity (oven dry)

4.1.1.3a Variation due to age and species

Results of NESTED ANOVA show that the interactions between age and species are not significant with respect to specific gravity (oven dry). While the species mean across ages was found to vary significantly from each other (5 % level). The results are presented in Table 8 and Figure 9.

Table 8. Mean wood specific gravity (oven dry) of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Specific gravity (oven dry)				
Pinus caribaea	0.512 (0.127)	0.554 (0.113)	0.637 (0.124)	0.499 (0.124)	0.550^{b} (0.129)
Pinus patula	0.566 (0.155)	0.566 (0.138)	0.612 (0.197)	0.555 (0.193)	0.575^{ab} (0.167)
Pinus oocarpa	0.606 (0.094)	0.627 (0.093)	0.615 (0.106)	0.671 (0.057)	0.630^{a} (0.089)
F value	0.88^{ns} (for comparing between age and species) 3.51* (for comparing species averaged over all ages)				
C.D	0.095 (for comparing species averaged over all ages)				

* Significant at 5 % level; ns non significant; C.D - critical difference; values within parentheses is standard deviation; means with same small letter as superscript in a column are homogeneous

The variation in specific gravity (oven dry) among species within different ages are presented in Table 8 and Figure 9A. From these it can be seen that in the 35

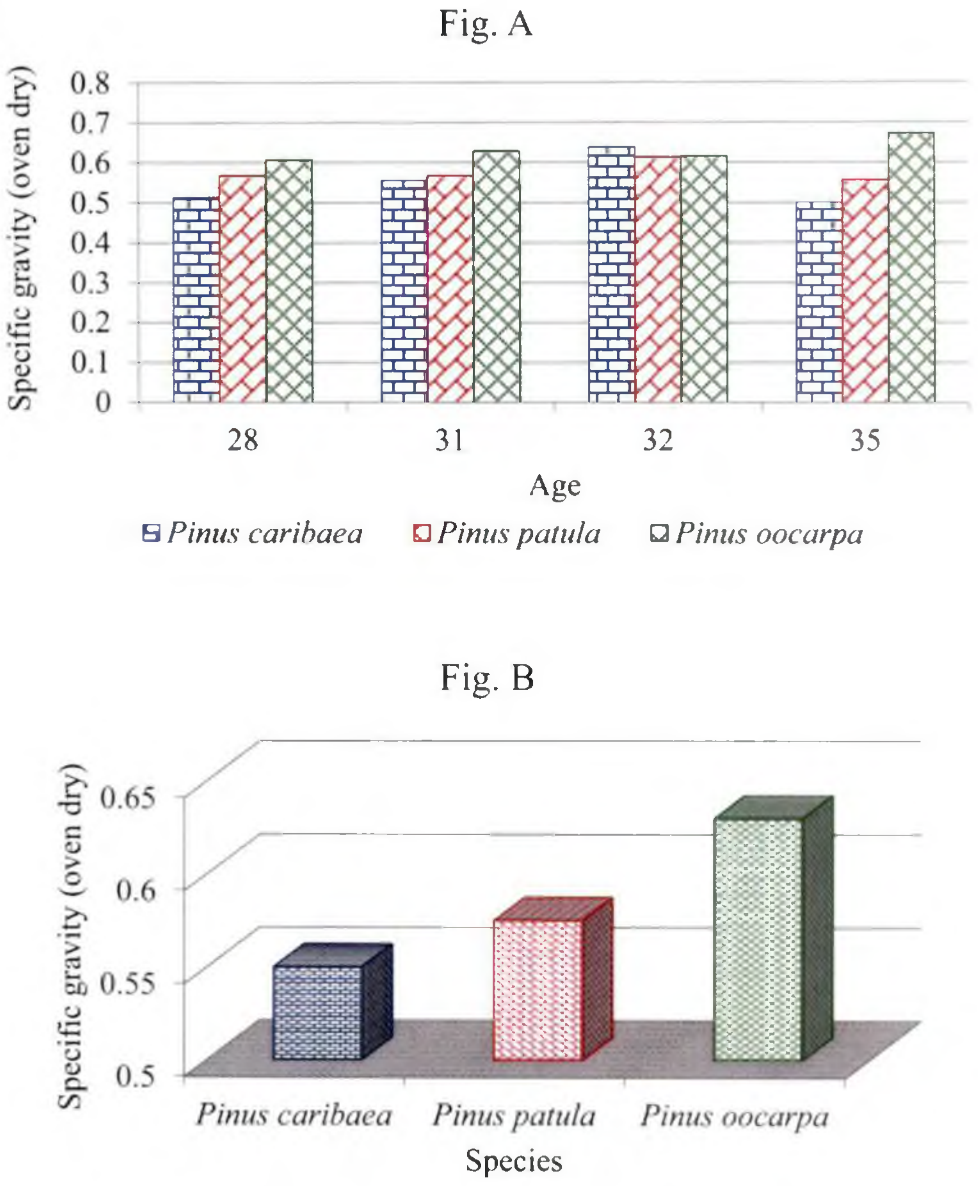

Fig. 9. Variation in specific gravity (oven dry) between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

years old plantation the specific gravity (oven dry) was found to range from 0.499 (*Pinus caribaea*) to 0.671 (*Pinus oocarpa*), in the 32 years old plantation it ranged from 0.612 (*Pinus patula*) to 0.637 (*Pinus caribaea*), in the 31 years old plantation it ranged from 0.554 (*Pinus caribaea*) to 0.627 (*Pinus oocarpa*) and in the 28 years old plantation it ranged from 0.512 (*Pinus caribaea*) to 0.606 (*Pinus oocarpa*).

In *Pinus caribaea* the values on specific gravity (oven dry) was found to range from 0.499 (35 years old plantation) to 0.637 (32 years old plantation). On the other hand in *Pinus patula* it was found to range from 0.555 (35 years old plantation) to 0.612 (32 years old plantation). The values ranged from 0.606 (28 years old plantation) to 0.671 (35 years old plantation) in *Pinus oocarpa* (Table 8 and Fig. 9A)

The species mean averaged over all ages showed significant difference among species at 5 per cent level (Table 8). *Pinus caribaea* had the lowest value (0.550) and *Pinus oocarpa* had the highest value (0.630). Also, there was significant difference between these two species with regard to specific gravity (oven dry) (Fig. 9B). But *Pinus patula* (0.575) was found to have no significant difference from the other two species.

4.1.1.3b Variation due to position in a species within an age group

Results pertaining to variation in oven dry specific gravity between positions in a species within an age group is summarized in Table 9 and Figure 10. Analysis of variance showed no significant difference between radial positions.

In 28 years old plantation, both *Pinus caribaea* and *Pinus patula* were found to have an increase in specific gravity (oven dry) values from pith to periphery position i.e. 0.424 to 0.607 and 0.413 to 0.752 respectively (Fig. 10A). However, in the case of *Pinus oocarpa*, the highest value was found to be in the periphery (0.681) and lowest value in the middle (0.573) position.

Table 9. Mean wood specific gravity (oven dry) at pith, middle and periphery of pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Specific gravity (oven dry)		
28	*Pinus caribaea*	0.424 (0.115)	0.462 (0.077)	0.607 (0.15)
	Pinus patula	0.413 (0.046)	0.637 (0.089)	0.752 (0.112)
	Pinus oocarpa	0.617 (0.171)	0.573 (0.031)	0.681 (0.015)
31	*Pinus caribaea*	0.545 (0.175)	0.495 (0.054)	0.677 (0.034)
	Pinus patula	0.467 (0.184)	0.560 (0.097)	0.787 (0.114)
	Pinus oocarpa	0.519 (0.025)	0.638 (0.03)	0.709 (0.093)
32	*Pinus caribaea*	0.671 (0.193)	0.563 (0.101)	0.622 (0.073)
	Pinus patula	0.571 (0.247)	0.478 (0.080)	0.671 (0.036)
	Pinus oocarpa	0.525 (0.095)	0.611 (0.046)	0.726 (0.018)
35	*Pinus caribaea*	0.434 (0.03)	0.457 (0.11)	0.649 (0.042)
	Pinus patula	0.355 (0.022)	0.559 (0.137)	0.647 (0.181)
	Pinus oocarpa	0.611 (0.023)	0.720 (0.053)	0.628 (0.049)
F value	1.60^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

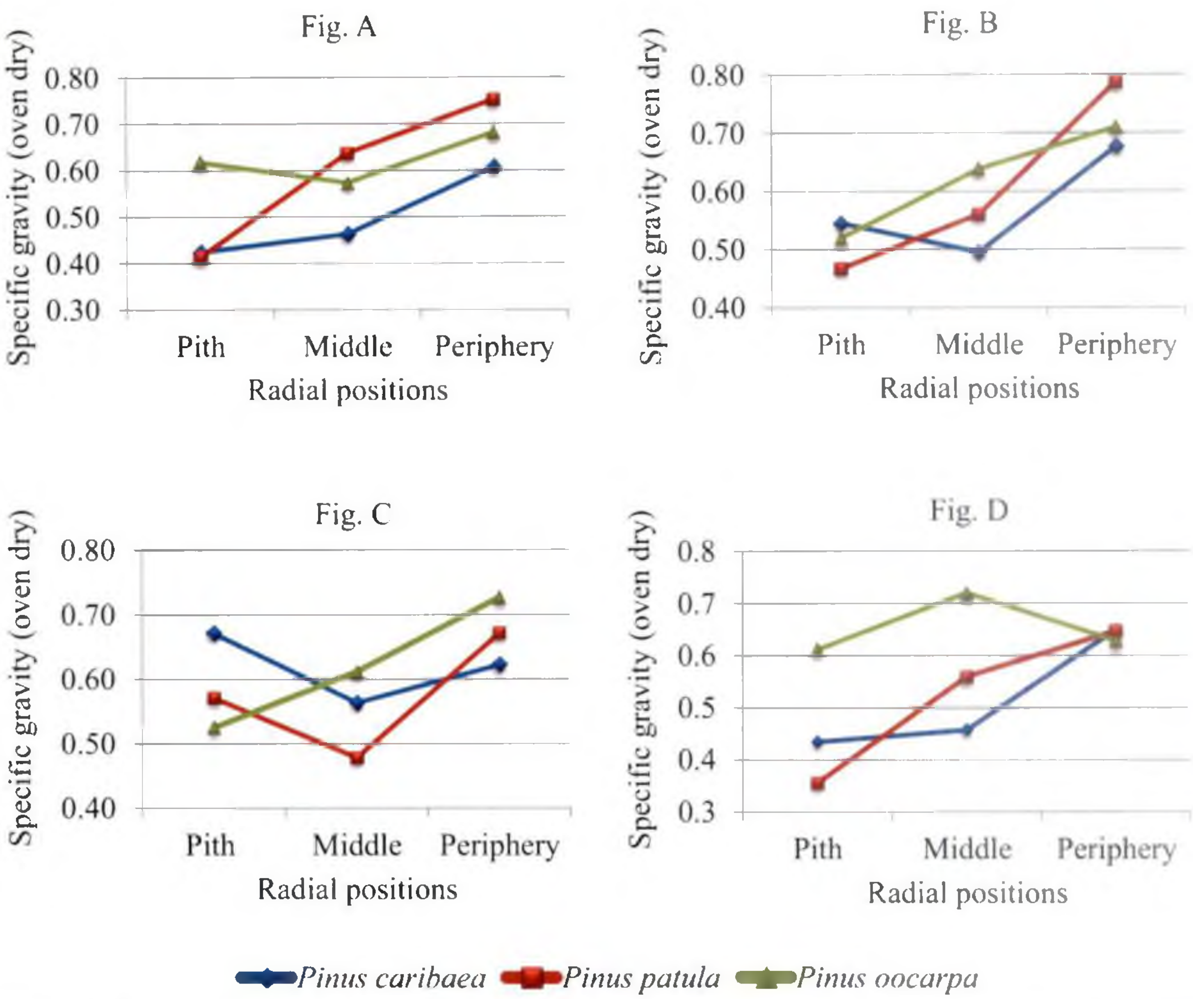

Fig. 10. Radial variation of specific gravity (oven dry) in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

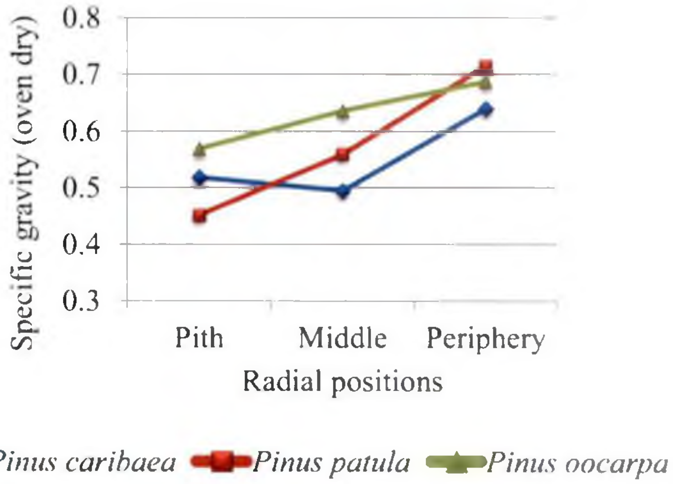

Fig. 11. Radial variation in mean specific gravity (oven dry) of pine species averaged over all ages

Pinus caribaea had specific gravity (oven dry) values varying from 0.495 (middle) to 0.677 (periphery) in 31 years old plantation. From Figure 10B it can be seen that the values were found to have an increasing trend from pith to periphery position in *Pinus patula* (0.467 to 0.787) and *Pinus oocarpa* (0.519 to 0.709) (Fig. 10B).

The species variation in specific gravity (oven dry) between radial positions in 32 years old plantation is graphically illustrated in Fig. 10C. From this it can found out that *Pinus caribaea* had values that range from 0.563 (middle) to 0.671 (pith). In *Pinus patula* it ranged from 0.478 (middle) to 0.671 (periphery) and in *Pinus oocarpa* it ranged from 0.525 (pith) to 0.726 (periphery).

Radial variation in 35 years old plantation species showed an increase in specific gravity (oven dry) from pith to periphery positions in *Pinus caribaea* (0.434 to 0.649) and *Pinus patula* (0.355 to 0.647) (Fig. 10D). However, in *Pinus oocarpa* the values ranged from 0.611 (pith) to 0.720 (middle).

4.1.1.3c Variation due to position within species averaged across all ages

The variation in radial positions of three pine species across all ages with respect to specific gravity (oven dry) is presented in Table 10 and Figure 11. From this it can be seen that both *Pinus patula* and *Pinus oocarpa* showed an increase in specific gravity from pith to periphery position and this variation is not influenced by age (Table 9). In *Pinus caribaea* and *Pinus patula* all the three positions varied significantly from each other. *Pinus caribaea* had values that varied from 0.494 (middle) to 0.639 (periphery). In *Pinus patula*, the values varied from 0.451 to 0.714. However, in *Pinus oocarpa* pith (0.568) and periphery (0.686) differed significantly from each other and the middle (0.635) position showed no significant difference from the other two positions.

Table 10. Mean wood specific gravity (oven dry) of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Specific gravity (oven dry)		
Pith	0.518^{b} (0.161)	0.451^{c} (0.157)	0.568^{b} (0.097)
Middle	0.494^{c} (0.087)	0.559^{b} (0.106)	0.635^{ab} (0.066)
Periphery	0.639^{a} (0.08)	0.714^{a} (0.12)	0.686^{a} (0.06)
F value	13.14** (for comparing between position within a species)		
C.D	0.099		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.2 ANATOMICAL PROPERTIES

4.2.1 Tracheid morphology

4.2.1.1 Tracheid length

4.2.1.1a Variation due to age and species

Results of analysis of variance show that the interactions between age and species are not significant with regard to tracheid length. The species variation in tracheid length was also found to be non significant among the three pine species. Results showing the comparison between age means of the same species, and between species means at the same age level are presented in Table 11 in Figure 12.

There was no significant difference between species within each age level with regard to tracheid length (Fig. 12A). Tracheid length was found to range from

3846.76 µm (*Pinus oocarpa*) to 4332.37 µm (*Pinus patula*) in the 28 years old plantation; in the 31 years old plantation, it ranged from 3530.88 µm (*Pinus caribaea*) to 4014.33 µm (*Pinus oocarpa*); in the 32 years old plantation it ranged from 4050.13 µm (*Pinus patula*) to 4557.14 µm (*Pinus caribaea*) and in the 35 years old plantation it ranged from 3280.52 µm (*Pinus patula*) to 3989.84 µm (*Pinus caribaea*).

Table 11. Mean tracheid length of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Tracheid length (µm)				
Pinus caribaea	4224.24 (892.03)	3530.88 (337.32)	4557.14 (1298.31)	3989.84 (758.29)	4076.48 (931.15)
Pinus patula	4332.37 (1046.94)	3758.94 (1169.25)	4050.13 (852.27)	3280.52 (902.00)	3855.49 (1034.72)
Pinus oocarpa	3846.76 (1285.85)	4014.33 (411.85)	4402.44 (563.19)	3751.01 (431.46)	4003.63 (771.63)
F value	1.81^{ns} (for comparing between age and species) 1.02^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

The variation in tracheid length due to age within a species was also found to be non significant among the three pine species (Table 11). The mean values are presented in Figure 12A. From this, it can be seen that both *Pinus caribaea* (4557.14 µm) and *Pinus oocarpa* (4402.44 µm) had higher values for tracheid length in 32 years old plantation. However, lowest values were noted in *Pinus caribaea* (3530.88 µm) in 31 years old plantation and in *Pinus oocarpa* (3751.01 µm) for 35 years old plantation. On the other hand, in *Pinus patula* the values ranged from 3280.52 µm (35 years old plantation) to 4332.37 µm (28 years old plantation).

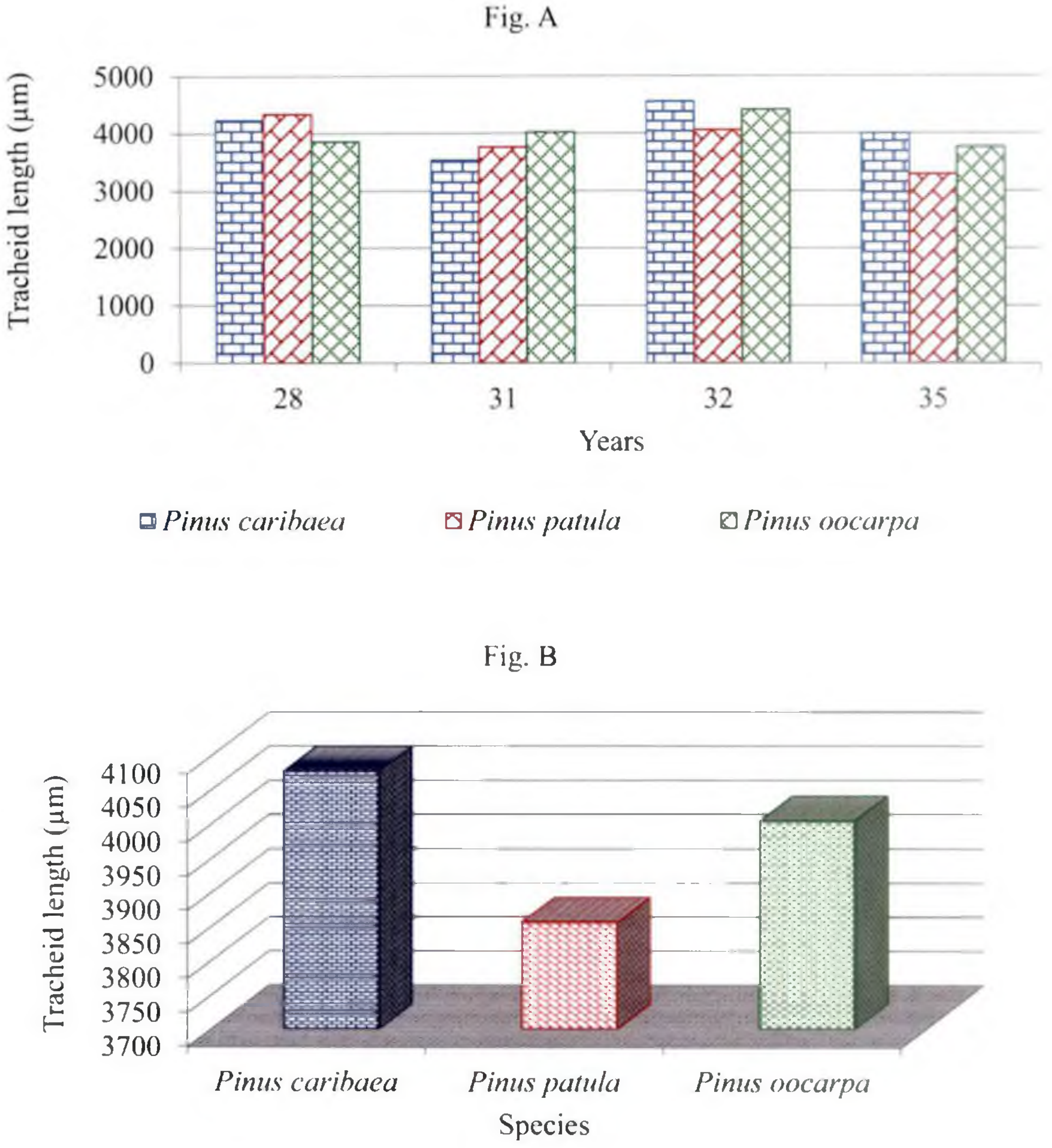

Fig. 12. Variation in tracheid length between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

A comparison of tracheid length averaged over all ages showed no significant difference between the three pine species (Fig. 12B). *Pinus caribaea* (4076.48 µm) had higher value followed by *Pinus oocarpa* (4003.63 µm). *Pinus patula* had a moderate value of 3855.49 µm.

4.2.1.1b Variation due to position in a species within an age group

The variation due to position in a species within age group was found to be significant (1% level). Hence, the comparison between positions within each species for each age level was done and the results are given in Table 12 and Figure 13.

In the 28 years old plantation, there was significant difference among radial positions in all the three pine species with respect to tracheid length (Table 12). From this it can be seen that both middle and periphery positions were found have homogenous values in both *Pinus patula* and *Pinus oocarpa.* However, these two positions differed significantly from pith in both these species. But in *Pinus caribaea* the pith differed significantly from the middle position, whereas periphery position was found to be homogenous with both pith and middle. There was an increase in tracheid length from pith to periphery position in both *Pinus patula* (3202.09 µm to 5023.07 µm) and *Pinus oocarpa* (2399.97 µm to 4752.69 µm). But in *Pinus caribaea* the tracheid length was found to increase from pith to middle (3284.03 µm to 4997.55 µm) and then it decreased at the periphery position (4391.15 µm). These radial variations among the three pine species are illustrated in Figure 13A.

Radial variation in 31 years old plantation showed no significant difference in both *Pinus caribaea* and *Pinus oocarpa*, whereas in *Pinus patula* pith differed significantly from middle and periphery, with regards to tracheid length. However the latter two positions had homogenous values in *Pinus patula.* From Figure 13B it can be seen that there is an increasing trend in tracheid length in *Pinus patula* and

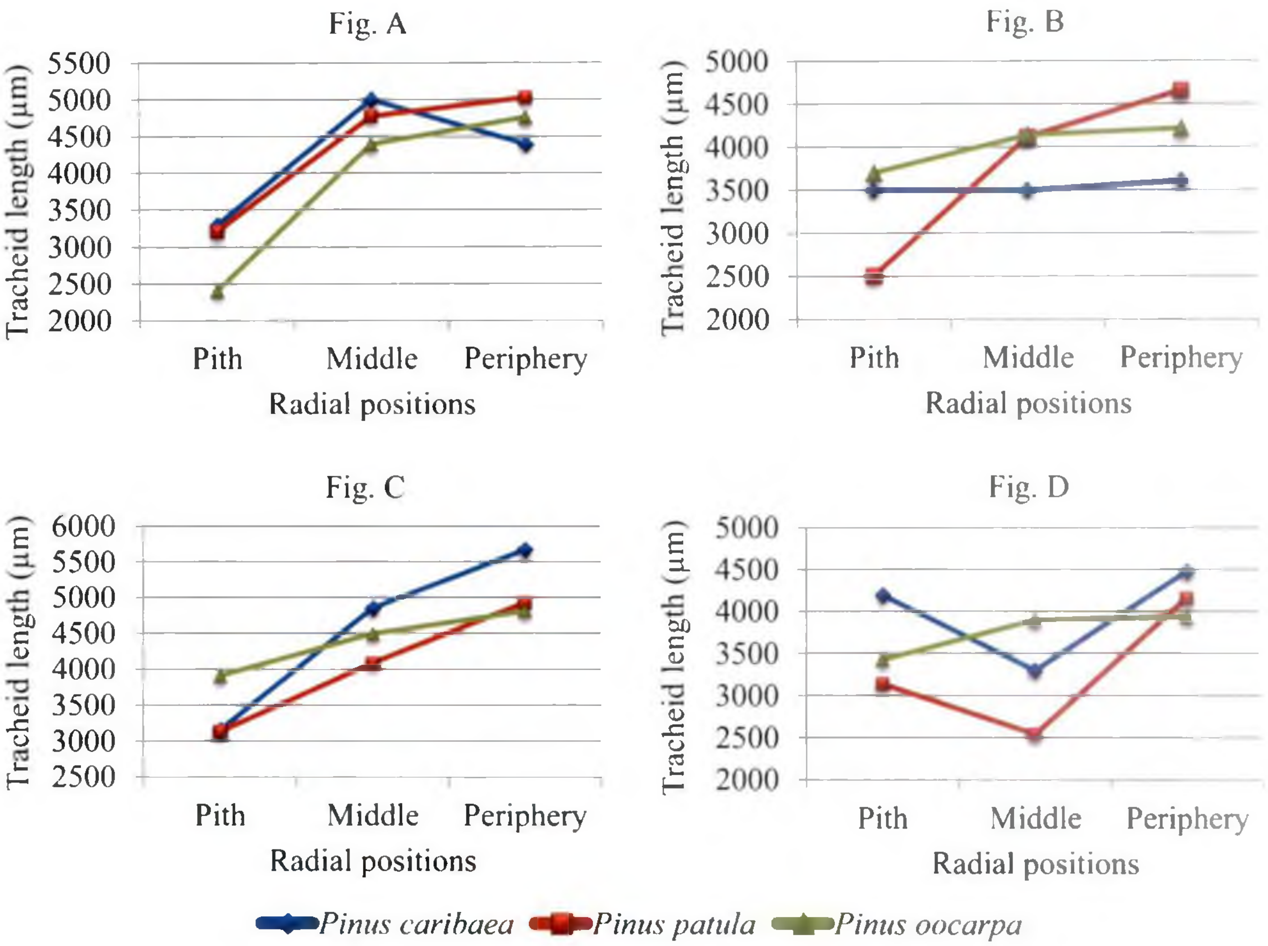

Fig. 13. Radial variation of tracheid length in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

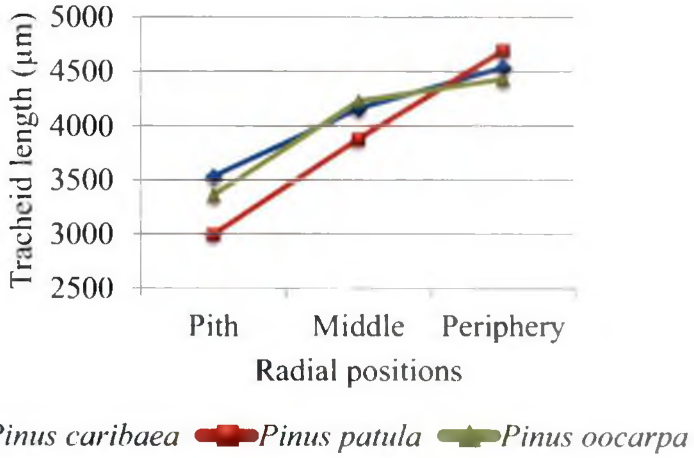

Fig. 14. Radial variation in mean tracheid length of pine species averaged over all ages

Table 12. Mean tracheid length at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Tracheid length (µm)		
28	*Pinus caribaea*	3284.03^{b} (659.20)	4997.55^{a} (640.34)	4391.15^{ab} (271.12)
	Pinus patula	3202.09^{b} (650.75)	4771.95^{a} (376.03)	5023.07^{a} (947.51)
	Pinus oocarpa	2399.97^{b} (200.50)	4387.60^{a} (578.20)	4752.69^{a} (1195.61)
31	*Pinus caribaea*	3494.29^{a} (584.54)	3492.35^{a} (271.18)	3606.61^{a} (169.19)
	Pinus patula	2506.20^{b} (32.63)	4116.07^{a} (1205.63)	4654.55^{a} (515.24)
	Pinus oocarpa	3693.95^{a} (317.71)	4136.35^{a} (118.83)	4212.69^{a} (572.81)
32	*Pinus caribaea*	3152.43^{b} (498.72)	4849.4^{a} (1187.65)	5669.59^{a} (372.71)
	Pinus patula	3133.76^{b} (282.39)	4090.13^{ab} (191.38)	4926.51^{a} (612.37)
	Pinus oocarpa	3907.49^{a} (716.62)	4492.77^{a} (190.86)	4807.04^{a} (305.77)
35	*Pinus caribaea*	4194.21^{a} (240.95)	3297.73^{a} (766.29)	4477.57^{a} (718.87)
	Pinus patula	3139.36^{ab} (982.31)	2541.57^{b} (413.16)	4160.61^{a} (328.62)
	Pinus oocarpa	3424.21^{a} (358.65)	3894.98^{a} (184.32)	3933.84^{a} (583.60)
F value	3.58** (for comparing between age and position within species)			
C.D	1204.72			

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

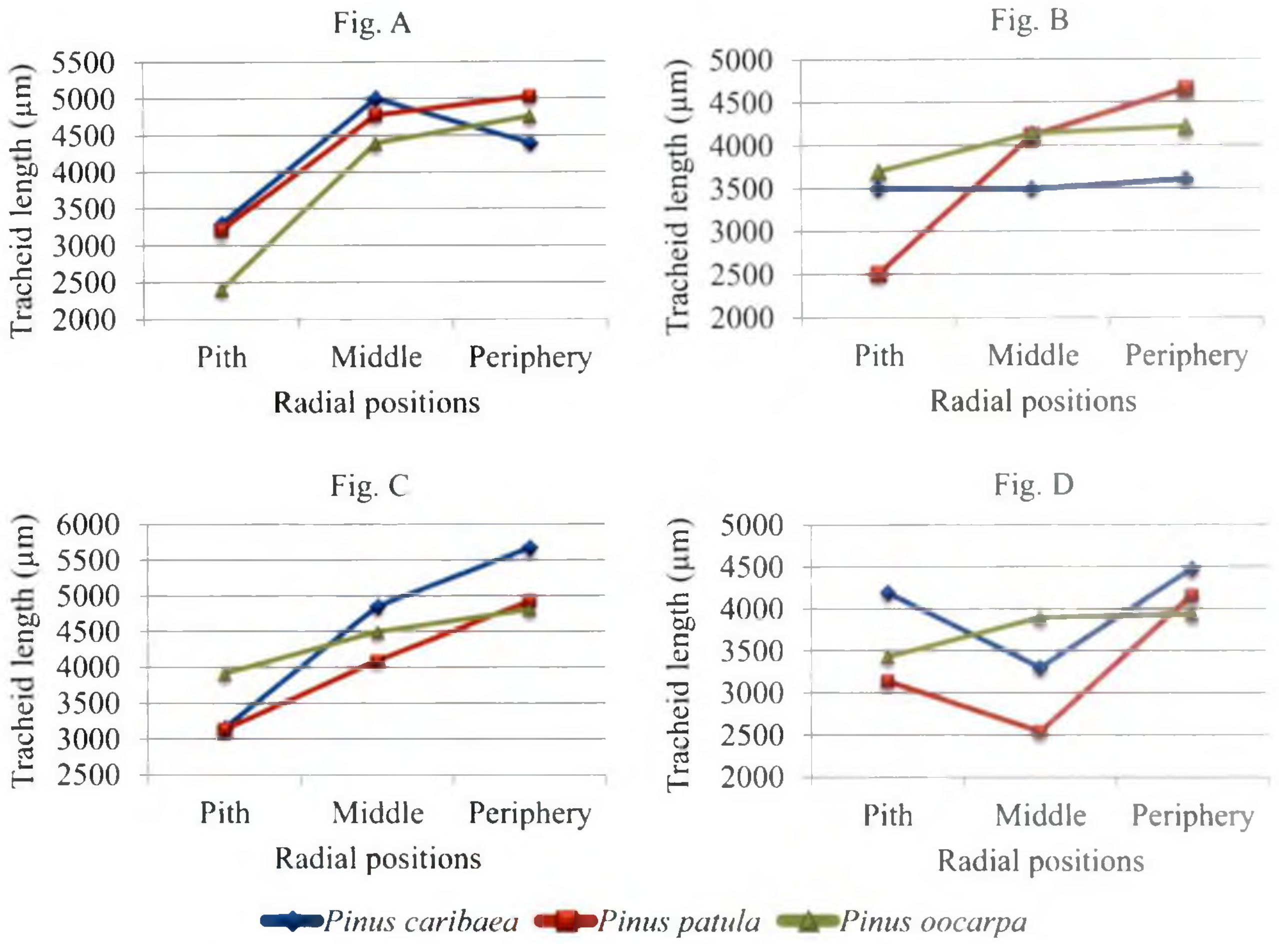

Fig. 13. Radial variation of tracheid length in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

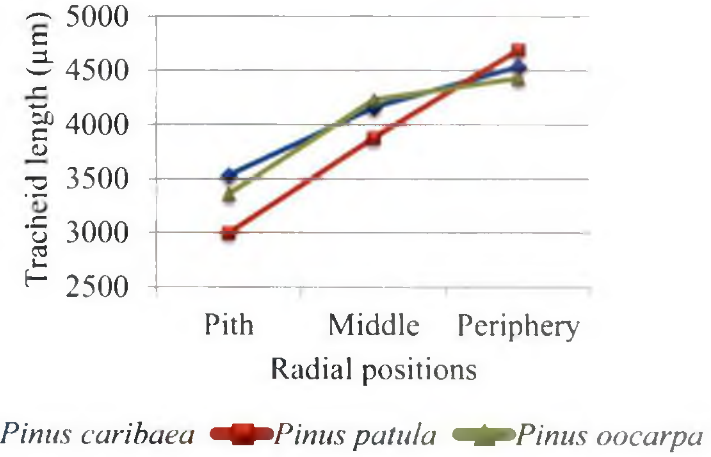

Fig. 14. Radial variation in mean tracheid length of pine species averaged over all ages

Pinus oocarpa from pith to periphery, whereas in *Pinus caribaea* it decreased from pith to middle and then increased at periphery position. In *Pinus caribaea* values were found to vary from 3492.35 μm to 3606.61 μm and in *Pinus patula* it varied from 2506.20 μm to 4654.55 μm. While in *Pinus oocarpa*, the values varied from 3693.95 μm to 4212.69 μm.

From Table 12, it can be seen that tracheid length in 32 years old plantation was found have no significant difference among the radial positions in *Pinus oocarpa.* But in *Pinus caribaea* tracheid length at pith differed significantly from both middle and periphery. The latter two positions were found to be homogenous in *Pinus caribaea*. *Pinus patula* also showed radial variation in tracheid length such that the pith differed significantly from the periphery position, while the middle position was found to be homogenous with pith and periphery. The mean values of tracheid length at pith, middle and periphery is presented graphically in Figure 13C. This shows an increasing trend in values from pith to periphery in all the three species. In *Pinus caribaea*, values were found to vary from 3152.43 μm to 5669.59 μm and in *Pinus patula* it varied from 3133.76 μm to 4926.51 μm. On the other hand, the values in *Pinus oocarpa* varied from 3907.49 μm to 4807.04 μm.

Radial variations in the three pines of 35 years age are presented in Table 12. This shows that there is no significant difference among the radial positions in *Pinus caribaea* and *Pinus oocarpa*, while in *Pinus patula*, the middle position differed significantly from periphery. But the pith positions had no significant difference from middle and periphery. The mean radial variation in the three pine species is illustrated graphically in Figure 13D. In both *Pinus caribaea* and *Pinus patula*, tracheid length was found to decrease from pith to middle position and then it increased at the periphery. *Pinus patula* had mean tracheid length of 3139.36 μm at pith, 2541.57 μm at middle and 4160.61 μm at periphery, while *Pinus caribaea* had values varying from 4194.21 μm at pith, 3297.73 μm at middle and 4477.57 μm at periphery position. On the other hand, *Pinus oocarpa* was found to have an increase in values from pith (3424.21 µm) to periphery (3933.84 µm).

4.2.1.1c Variation due to position within species averaged across all ages

Results of analysis of variance conducted showed highly significant variation in tracheid length with respect to position within each species (1% level). Here, species mean averaged across all the ages in different radial positions were taken for comparison (Table 13 and Fig. 14).

Table 13. Mean tracheid length of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Tracheid length (µm)		
Pith	3531.24^b (610.70)	2995.35^c (595.75)	3356.41^b (712.08)
Middle	4159.26^a (1047.10)	3879.93^b (1029.79)	4227.93^a (367.09)
Periphery	4536.08^a (851.04)	4691.18^a (649.31)	4426.57^a (738.69)
F value	17.17** (for comparing between position within a species)		
C.D	602.36		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

From Table 13, it can be seen that the tracheid length values were found to show an increasing trend from pith to periphery position in all the three species. But this variation in radial position within the species is also influenced by age (Table 12). In *Pinus caribaea* pith (3531.24 µm) differed significantly from middle (4159.26 µm)

Fig. A

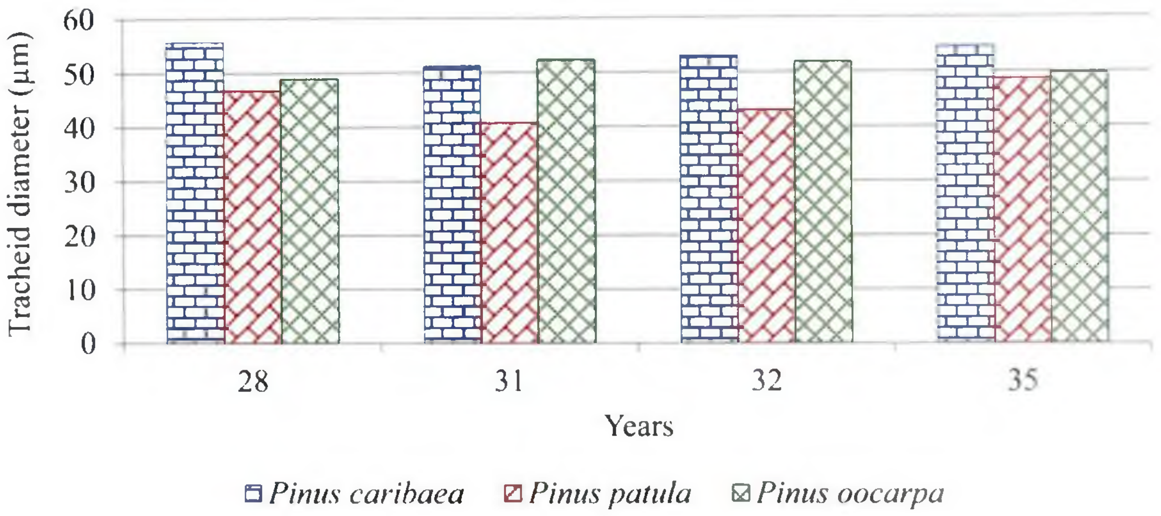

Fig. B

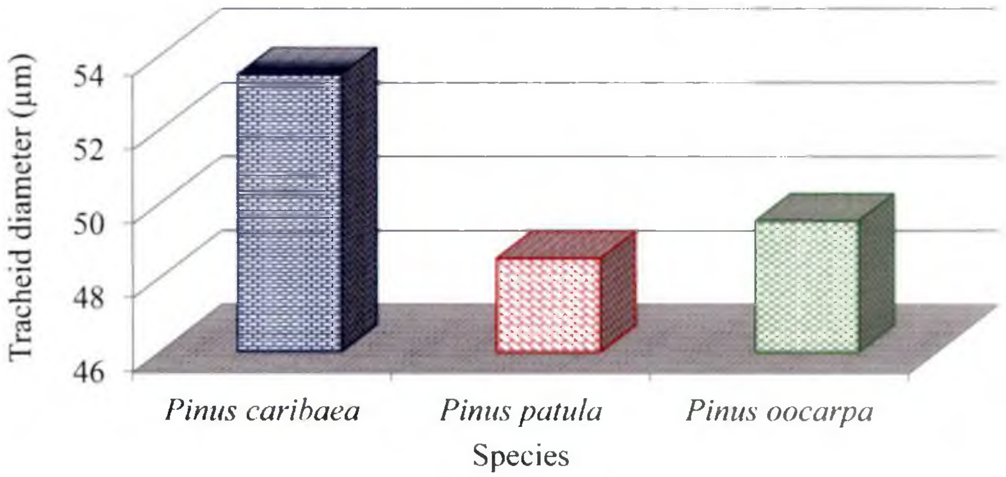

Fig. 15. Variation in tracheid diameter between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

and periphery (4536.08 μm). *Pinus oocarpa* also showed similar radial variation in which middle (4227.93 μm) and periphery (4426.57 μm) was found to differ significantly from pith (3356.41 μm). In both these species the middle and periphery were found to be homogeneous in mean tracheid length. While in *Pinus patula* all the three positions differed significantly with each other with values ranging from 2995.35 μm at pith, 3879.93 μm at middle and 4691.18 μm at periphery.

4.2.1.2 Tracheid diameter

4.2.1.2a Variation due to age and species

The data on variation in tracheid diameter with respect to age and species is presented in Table 14 and Figure 15. Analysis of variance revealed that age and species interactions were not significant. Hence, the effect of age is not varying with species within an age and between different ages within a species. On the other hand, the species variation across all ages was found to be highly significant at 1 per cent level of variation.

Tracheid diameter among species was found to range in the 28 years old plantation from 46.69 μm (*Pinus patula*) to 55.61 μm (*Pinus caribaea*). In the 31 years old plantation, it ranged from 40.62 μm (*Pinus patula*) to 52.13 μm (*Pinus oocarpa*) and in the 32 years old plantation it ranged from 42.89 μm (*Pinus patula*) to 52.86 μm (*Pinus caribaea*) and in 35 years old plantation it ranged from 54.39 μm (*Pinus caribaea*) to 48.52 μm (*Pinus patula*). These results are presented in Table 14 and Figure 15A.

From Table 14 and Figure 15A it can be seen that the tracheid diameter was found to range in *Pinus caribaea* from 51.13 μm (31 years old plantation) to 55.61 μm (28 years old plantation). In *Pinus patula*, it ranged from 40.62 μm (31 years old plantation) to 48.52 μm (35 years old plantation) and in *Pinus oocarpa* it was found to range from 48.82 μm (28 years old plantation) to 52.13 μm (31 years old plantation).

Table 14. Mean tracheid diameter of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Tracheid diameter (μm)				
Pinus caribaea	55.61 (6.55)	51.13 (5.86)	52.86 (8.29)	54.39 (8.03)	53.49^{a} (7.14)
Pinus patula	46.69 (7.38)	40.62 (6.38)	42.89 (4.72)	48.52 (4.43)	48.52^{b} (4.43)
Pinus oocarpa	48.82 (8.72)	52.13 (5.81)	51.74 (6.59)	49.53 (6.10)	49.53^{b} (6.10)
F value	1.44^{ns} (for comparing between age and species) 16.25** (for comparing species averaged over all ages)				
C.D	4.86 (for comparing species averaged over all ages)				

** Significant at 1% level; ns - non significant; C.D - critical difference; values within parentheses is standard deviation; means with same small letter as superscript in a column are homogeneous

Species variation in tracheid diameter averaged over all ages was found to be highly significant at 1 per cent level. These results are presented in Table 14 and Figure 15B. From this it can be found that *Pinus caribaea* (53.49 μm) differed significantly from *Pinus oocarpa* (49.53 μm) and *Pinus patula* (48.52 μm). The latter two species had no significant difference with respect to tracheid diameter (Table 14).

4.2.1.2b Variation due to position in a species within an age group

There is no significant difference in the interactions between age and position within a species. The summarized results are presented in Table 15 and Figure 16.

Fig. A

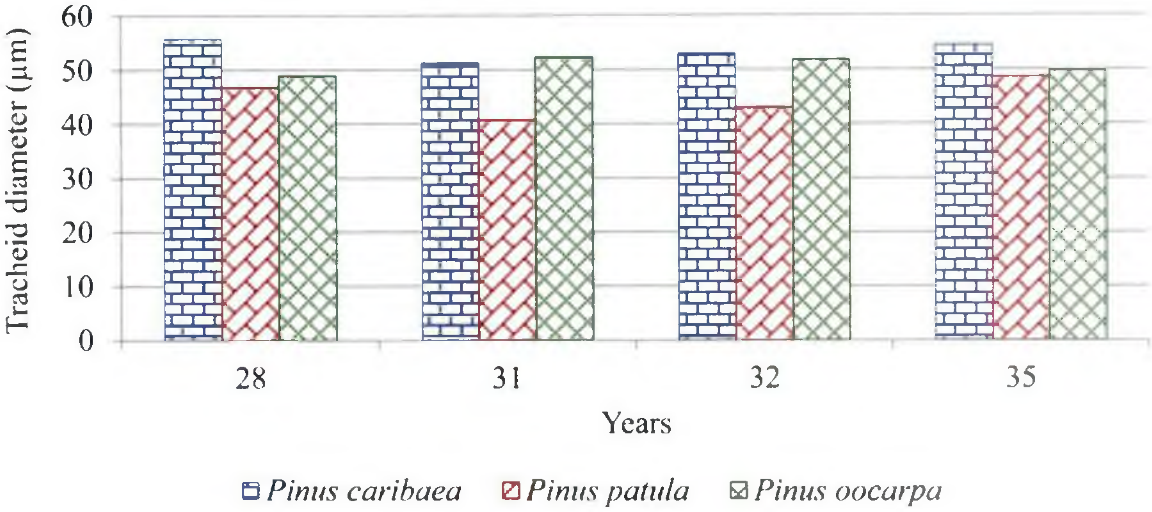

Fig. B

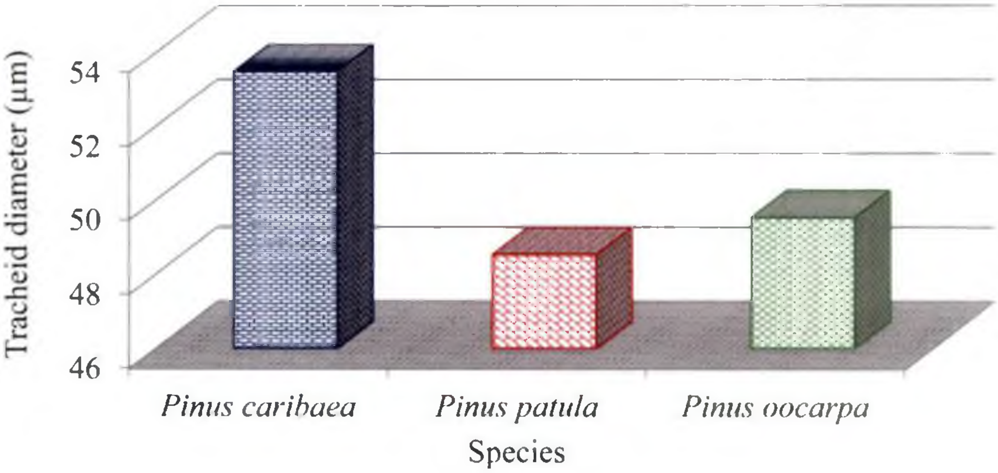

Fig. 15. Variation in tracheid diameter between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

Table 15. Mean tracheid diameter at pith, middle and periphery of pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Tracheid diameter (µm)		
28	*Pinus caribaea*	50.84 (6.20)	59.61 (4.51)	56.38 (7.35)
	Pinus patula	41.17 (7.45)	48.34 (7.28)	50.56 (6.10)
	Pinus oocarpa	41.27 (1.74)	49.90 (4.34)	55.29 (11.48)
31	*Pinus caribaea*	56.14 (2.39)	51.16 (7.35)	46.09 (1.24)
	Pinus patula	35.95 (2.63)	41.80 (0.93)	44.11 (10.11)
	Pinus oocarpa	51.29 (6.12)	52.27 (1.31)	52.84 (9.71)
32	*Pinus caribaea*	43.95 (2.53)	53.08 (5.87)	61.54 (1.38)
	Pinus patula	38.09 (0.74)	43.60 (4.16)	46.99 (3.27)
	Pinus oocarpa	47.33 (1.74)	52.37 (8.73)	55.54 (6.58)
35	*Pinus caribaea*	51.02 (1.26)	53.35 (8.41)	58.81 (11.73)
	Pinus patula	46.65 (1.06)	46.96 (5.41)	51.97 (4.62)
	Pinus oocarpa	48.62 (6.59)	49.89 (1.90)	50.08 (9.99)
F value	1.47^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

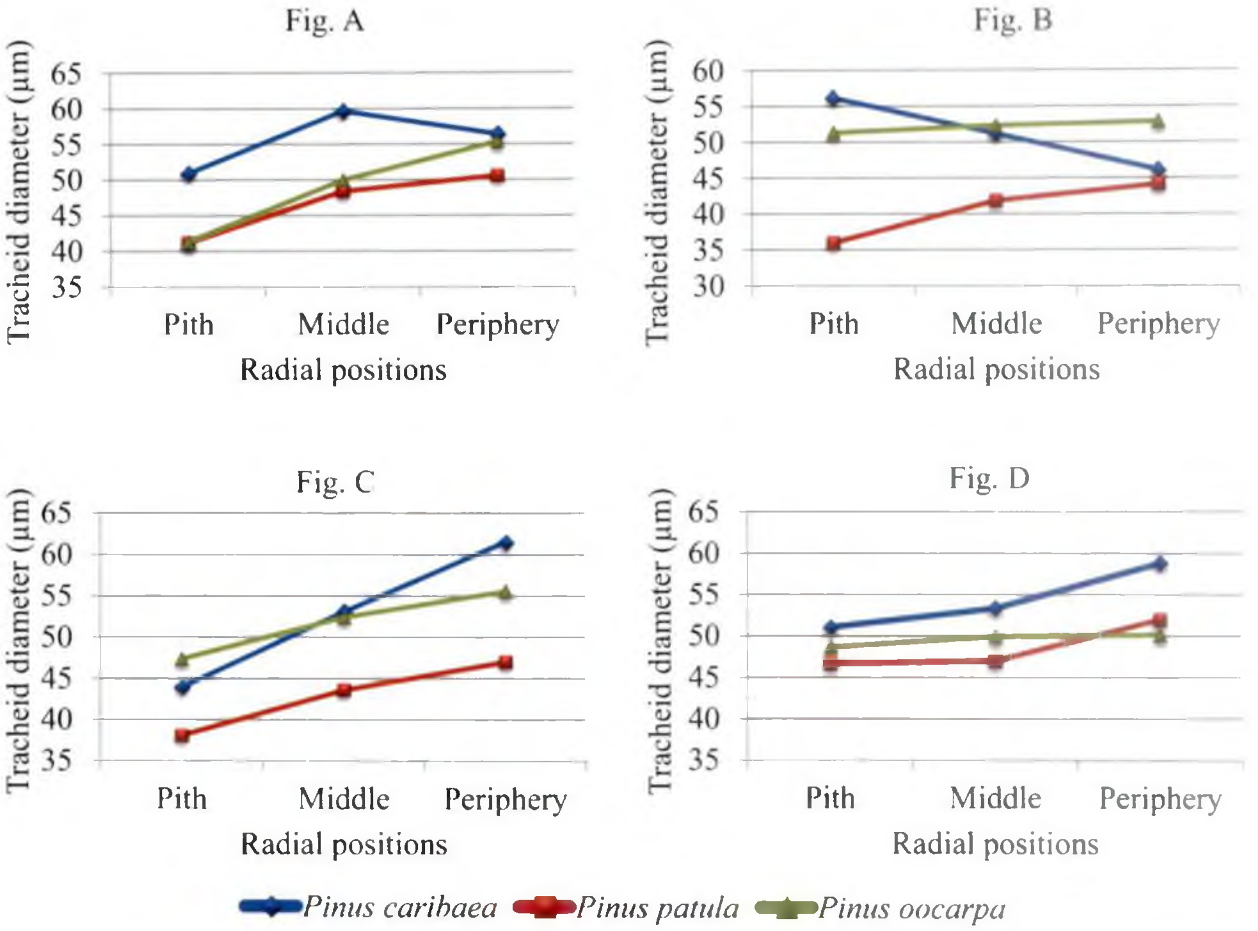

Fig. 16. Radial variation of tracheid diameter in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

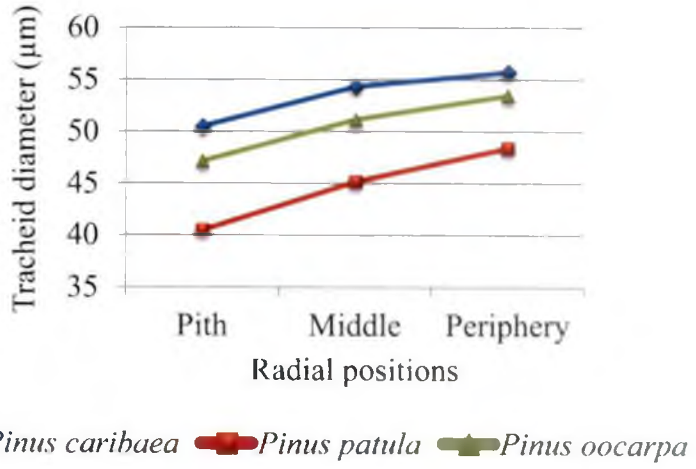

Fig. 17. Radial variation in mean tracheid diameter of pine species averaged over all ages

The values showed an increasing trend in tracheid diameter from pith to periphery in *Pinus patula* (41.17 µm to 50.56 µm) and *Pinus oocarpa* (41.27 µm to 55.29 µm) belonging to 28 years old plantation (Fig. 16A). But in *Pinus caribaea* it first increased from pith (50.84 µm) to middle position (59.61 µm) and decreased in the periphery position (56.38 µm).

From Figure 16B it can be seen that in 31 years old plantation the tracheid diameter showed an increase from pith to periphery position in *Pinus patula* and *Pinus oocarpa* i.e. 35.95 µm to 44.11 µm and 51.29 µm to 52.84 µm respectively. But in *Pinus caribaea*, the value was found to decrease from pith (56.14 µm) to periphery position (46.09 µm).

In the 32 years old plantation, tracheid diameter was found to have an increase from pith to periphery in all the three pine species that were studied (Fig. 16C). In *Pinus caribaea* it varied from 43.95 µm to 61.54 µm and in *Pinus patula* it was from 38.09 µm to 46.99 µm. On the other hand, in *Pinus oocarpa* it varied from 47.33 µm to 55.54 µm.

The tracheid diameter was found to increase in all the three pine species from pith to periphery position in 35 years old plantation (Fig. 16D). *Pinus caribaea* was found to have values ranging from 51.02 µm (pith) to 58.81 µm (periphery). The values varied from 46.65 µm (pith) to 51.97 µm (periphery) in *Pinus patula*, whereas in *Pinus oocarpa* it varied from 48.62 µm (pith) to 50.08 µm (periphery).

4.2.1.2c Variation due to position within species averaged across all ages

The summarized data on variation of tracheid diameter in radial positions of the three species across all ages are presented in Table 16 and graphically shown in Figure 17. Analysis of variance conducted revealed that the variation between species is highly significant at 1 per cent level and age did not have any influence on this variation (Table. 15).

Table 16. Mean tracheid diameter of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Tracheid diameter (μm)		
Pith	50.49^{a} (5.47)	40.47^{b} (5.41)	47.13^{b} (5.52)
Middle	54.30^{a} (6.61)	45.17^{ab} (5.06)	51.11^{ab} (4.46)
Periphery	55.71^{a} (8.53)	48.41^{a} (6.44)	53.44^{a} (8.51)
F value	4.10** (for comparing between position within a species)		
C.D	6.25		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

From Figure 17, it can be seen that there is an increasing trend in tracheid diameter values from pith to periphery position in all the three species that were studied. In *Pinus caribea*, the pith (50.49 μm), middle (54.30 μm) and periphery (55.71 μm) position was found to be homogenous. But in *Pinus patula*, the pith position (40.47 μm) differed significantly from periphery (48.41 μm), while the middle position (45.17 μm) was found to be homogenous with both pith and periphery. *Pinus oocarpa* also showed similar radial variation such that the pith (47.13 μm) was found to differ significantly from periphery (53.44 μm). On the other hand, the middle (51.11 μm) position was found to be homogenous with the other two radial positions.

4.2.1.3 Tracheid wall thickness

4.2.1.3a Variation due to age and species

Results of analysis of variance showed that the interactions between age and species are not significant with respect to tracheid wall thickness. Species mean across all ages was also found to be non significant among the three pine species. The results are presented in Table 17 and Figure 18.

Table 17. Mean tracheid wall thickness of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Tracheid wall thickness (μm)				
Pinus caribaea	4.94 (1.51)	5.28 (1.53)	4.27 (1.38)	6.05 (2.16)	5.13 (1.73)
Pinus patula	4.28 (1.43)	5.21 (2.77)	4.12 (1.61)	6.31 (3.91)	4.98 (2.66)
Pinus oocarpa	4.52 (1.05)	6.39 (2.49)	5.68 (1.97)	5.41 (2.21)	5.50 (2.03)
F value	2.07^{ns} (for comparing between age and species) 1.46^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

From Table 17 it can be seen that in the 28 years old plantation, the tracheid wall thickness was found to range from 4.28 μm (*Pinus patula*) to 4.94 μm (*Pinus caribaea*). In the 31 years old plantation it ranged from 5.21 μm (*Pinus patula*) to 6.39 μm (*Pinus oocarpa*) and in the 32 years old plantation it ranged from 4.12 μm (*Pinus patula*) to 5.68 μm (*Pinus oocarpa*). In the 35 years old plantation tracheid wall thickness ranged from 5.41 μm (*Pinus oocarpa*) to 6.31 μm (*Pinus patula*). The results are illustrated graphically in Figure 18A.

Fig. A

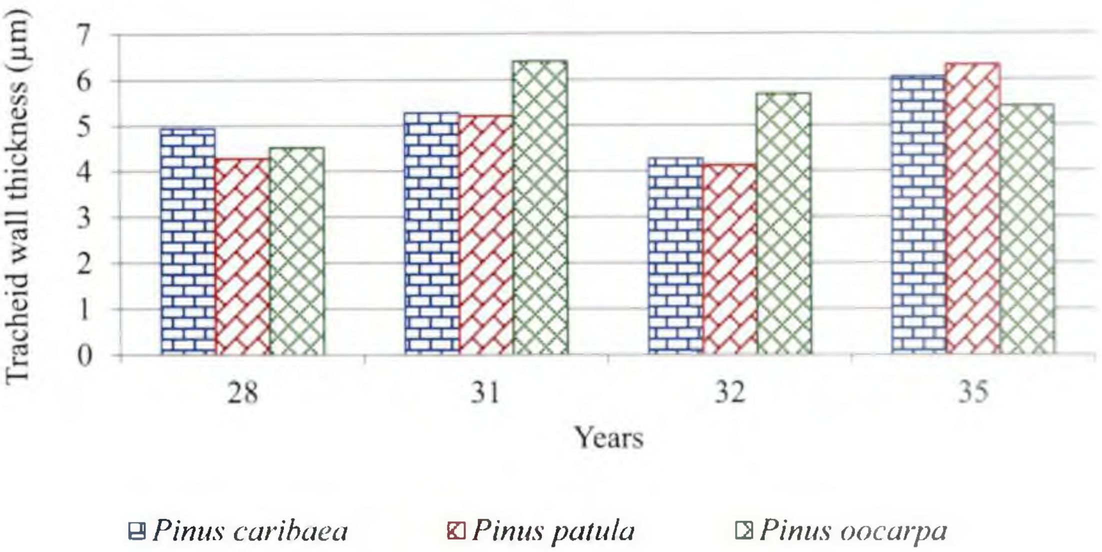

Fig. B

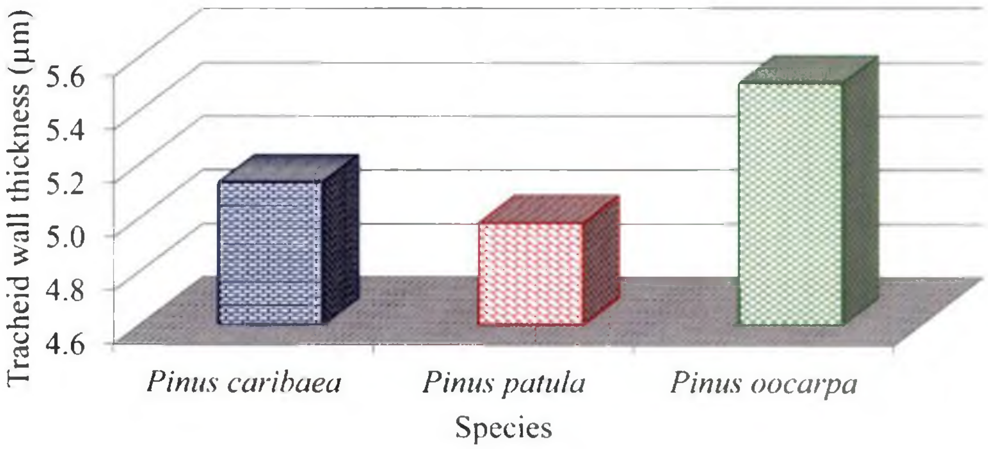

Fig. 18. Variation in tracheid wall thickness between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

In *Pinus caribaea* the values on tracheid wall thickness was found to vary from 4.27 µm (32 years old plantation) to 6.05 µm (35 years old plantation) and in *Pinus patula* it ranged from 4.12 µm (32 years old plantation) to 6.31 µm (35 years old plantation). On the other hand, in *Pinus oocarpa,* tracheid wall thickness was found to range from 4.52 µm (28 years old plantation) to 6.39 µm (31 years old plantation) (Fig. 18A)

The species mean on tracheid wall thickness averaged over all ages showed no significant difference among the three pines (Table 8). From Figure 18B it can be found that *Pinus patula* had the lowest value (4.98 µm) and *Pinus oocarpa* had the highest value (5.50 µm). However, *Pinus caribaea* (5.13 µm) had a moderate value for tracheid wall thickness.

4.2.1.3b Variation due to position in a species within an age group

Results pertaining to variation in tracheid wall thickness between positions in a species within an age group is summarized in Table 18 and illustrated in Figure 19. Analysis of variance showed that there is no statistical significant difference between the three radial positions within an age group.

In 28 years old plantation, all the three pine species had an increase in tracheid wall thickness from pith to periphery. The values varied from 3.79 µm to 6.41 µm in *Pinus caribaea* and 3.20 µm to 5.86 µm in *Pinus patula.* In the case of *Pinus oocarpa* it varied from 3.76 µm to 5.33 µm (Fig. 19A).

The radial distribution pattern showed an increasing trend from pith to periphery with respect to tracheid wall thickness in all the three pine species at 31 years old plantation (Fig. 19B). *Pinus caribaea* had tracheid wall thickness values ranged from 4.84 µm to 5.96 µm and in *Pinus patula* it ranged from 1.88 µm to

Table 18. Mean tracheid wall thickness at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Tracheid wall thickness (µm)		
28	*Pinus caribaea*	3.79 (1.01)	4.61 (1.45)	6.41 (0.75)
	Pinus patula	3.20 (0.11)	3.77 (0.73)	5.86 (1.33)
	Pinus oocarpa	3.76 (0.21)	4.48 (0.99)	5.33 (1.23)
31	*Pinus caribaea*	4.84 (1.15)	5.06 (0.30)	5.96 (2.63)
	Pinus patula	1.88 (0.34)	6.59 (2.25)	7.16 (0.59)
	Pinus oocarpa	4.98 (1.28)	5.72 (1.12)	8.48 (3.41)
32	*Pinus caribaea*	2.63 (0.87)	4.93 (0.65)	5.24 (0.64)
	Pinus patula	2.46 (0.75)	4.80 (1.82)	5.09 (0.44)
	Pinus oocarpa	3.89 (0.90)	5.98 (1.93)	7.18 (1.61)
35	*Pinus caribaea*	5.40 (0.59)	5.14 (2.05)	7.61 (2.93)
	Pinus patula	3.53 (1.46)	5.40 (3.57)	9.99 (3.65)
	Pinus oocarpa	4.19 (0.99)	4.77 (0.98)	7.26 (3.10)
F value	0.76^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

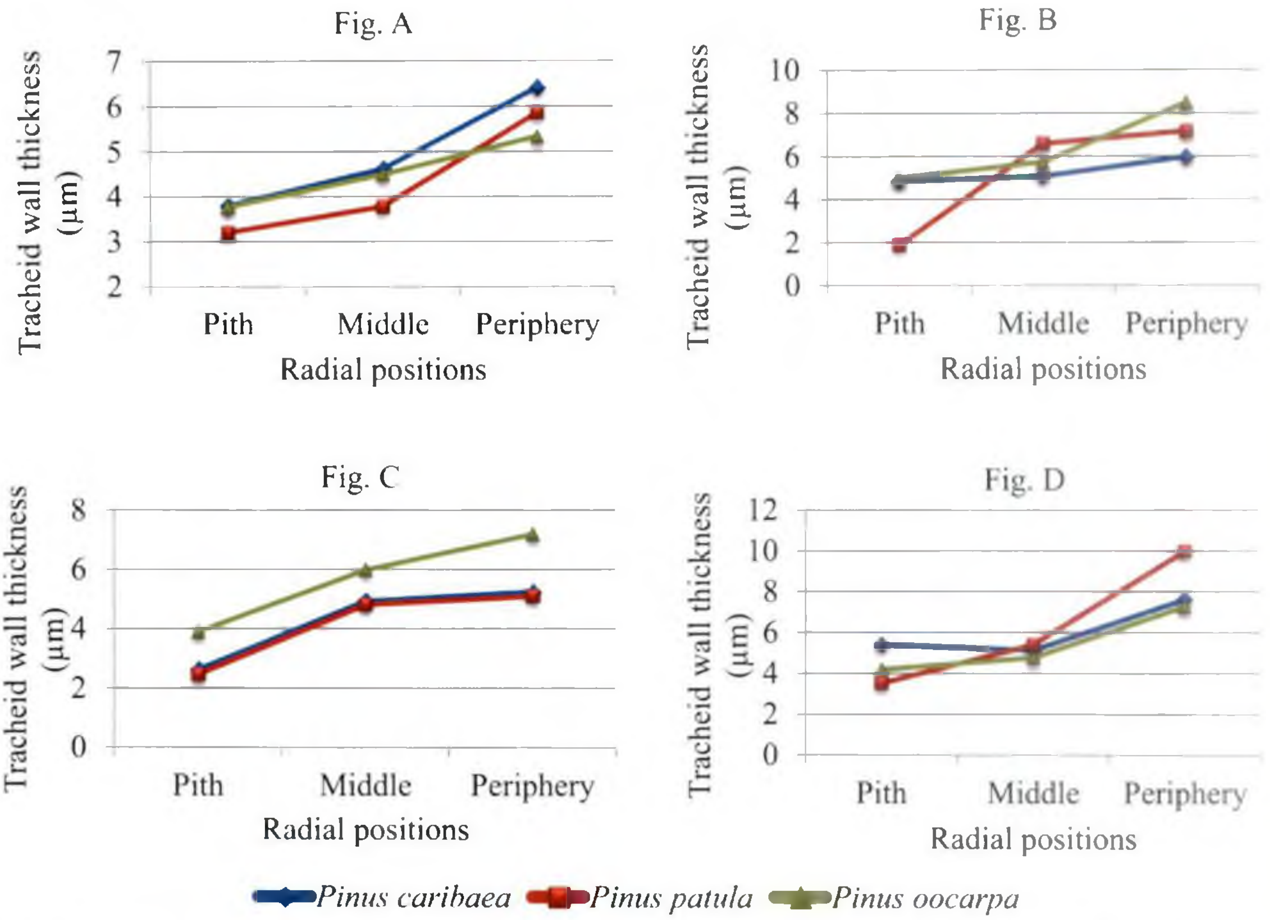

Fig. 19. Radial variation of tracheid wall thickness in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

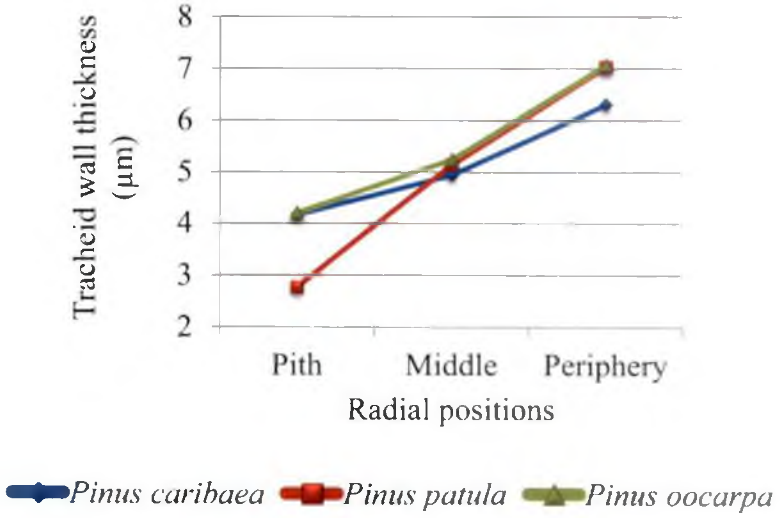

Fig. 20. Radial variation in mean tracheid wall thickness of pine species averaged over all ages

7.16 µm. The tracheid wall thickness was found to have values ranging from 4.98 µm to 8.48 µm in *Pinus oocarpa.*

The tracheid wall thickness of the three pine species, belonging to 32 years old plantation, at each radial position is graphically illustrated in Figure 19C. From this, it can found out that the three pine species showed an increase in tracheid wall thickness from pith to periphery. *Pinus caribaea* had values that ranged from 2.63 µm to 5.24 µm. In *Pinus patula* it ranged from 2.46 µm to 5.09 µm and in *Pinus oocarpa* it ranged from 3.89 µm to 7.18 µm.

Radial positions in 35 years old plantation showed an increase in tracheid wall thickness from pith to periphery in *Pinus patula* (3.53 µm to 9.99 µm) and *Pinus oocarpa* (4.19 µm to 7.26 µm) (Fig. 19D). However, in *Pinus caribaea* the values were found to decrease from pith (5.40 µm) to middle (5.14 µm) position and then increase to the periphery (7.61 µm).

4.2.1.3c Variation due to position within species averaged across all ages

The variation in radial positions of the three pine species across all ages with respect to tracheid wall thickness is presented in Table 19 and Figure 20. Analysis of variance showed that there exists significant differences among radial positions within each species (1 % level).

From Figure 20, it can be seen that all the three species showed increase in tracheid wall thickness from pith to periphery position and this variation is not influenced by age (Table 18). *Pinus caribaea* was found to have significant difference between pith (4.16 µm) and periphery (6.30 µm), while the middle position (4.94 µm) was found to be homogenous with the other two radial positions. *Pinus oocarpa* also showed similar variation. In this species, pith (4.20 µm) differed significantly from periphery (7.06 µm) and middle position (5.24 µm) was found to be homogenous with the other two radial positions. On the other hand, the pattern of radial variation was different in *Pinus patula* in which there is no significant difference between middle (5.14) and periphery (7.03 µm), while pith (2.77 µm) position was found to have a significant difference in tracheid wall thickness from the other two radial positions.

Table 19. Mean tracheid wall thickness of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Tracheid wall thickness (µm)		
Pith	4.16^{b} (1.36)	2.77^{b} (0.98)	4.20^{b} (0.94)
Middle	4.94^{ab} (1.13)	5.14^{a} (2.25)	5.24^{ab} (1.30)
Periphery	6.30^{a} (1.95)	7.03^{a} (2.57)	7.06^{a} (2.45)
F value	9.25** (for comparing between position within a species)		
C.D	2.01		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.2.1.4 Tracheid lumen diameter

4.2.1.4a Variation due to age and species

The result of analysis of variance indicates that there is no statistically significant difference in tracheid lumen diameter due to age and species interactions. This implies that there is no variation between species within an age group and between different ages within a species. But the species variation across the age was found to have highly significant difference between the three pine species at 1 per cent variance level. These results are presented in Table 20 and illustrated in Figure 21.

Table 20. Mean tracheid lumen diameter of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Tracheid lumen diameter (µm)				
Pinus caribaea	45.74 (6.20)	40.56 (7.17)	44.32 (6.35)	42.29 (9.46)	43.23^{a} (7.36)
Pinus patula	38.13 (6.85)	30.20 (5.72)	34.66 (4.51)	35.91 (4.77)	34.73^{b} (6.05)
Pinus oocarpa	39.77 (8.26)	39.35 (8.82)	40.38 (7.02)	38.72 (8.77)	39.55^{ab} (7.91)
F value	0.41^{ns} (for comparing between age and species) 9.81** (for comparing species averaged over all ages)				
C.D	5.936				

** Significant at 1 % level; ns - non significant; C.D - critical difference; values within parentheses is standard deviation

In 28 years old plantation, *Pinus caribaea* (45.74 µm) was found to have higher values for tracheid lumen diameter, while *Pinus patula* (38.13 µm) had the lowest value for it. In 31 years old plantation, it ranged from 40.56 µm (*Pinus caribaea*) to 30.20 µm (*Pinus patula*), in 32 years old plantation it ranged from 44.32 µm (*Pinus caribaea*) to 34.66 µm (*Pinus patula*) and in 35 years old plantation it ranged from 42.29 µm (*Pinus caribaea*) to 35.91 µm (*Pinus patula*). Figure 21A gives a picture of species variation within each age group with respect to tracheid lumen diameter. From this, it can be seen that the higher and lower values were found to be associated respectively with *Pinus caribaea* and *Pinus patula*. While in all the four age groups *Pinus oocarpa* had only moderate values.

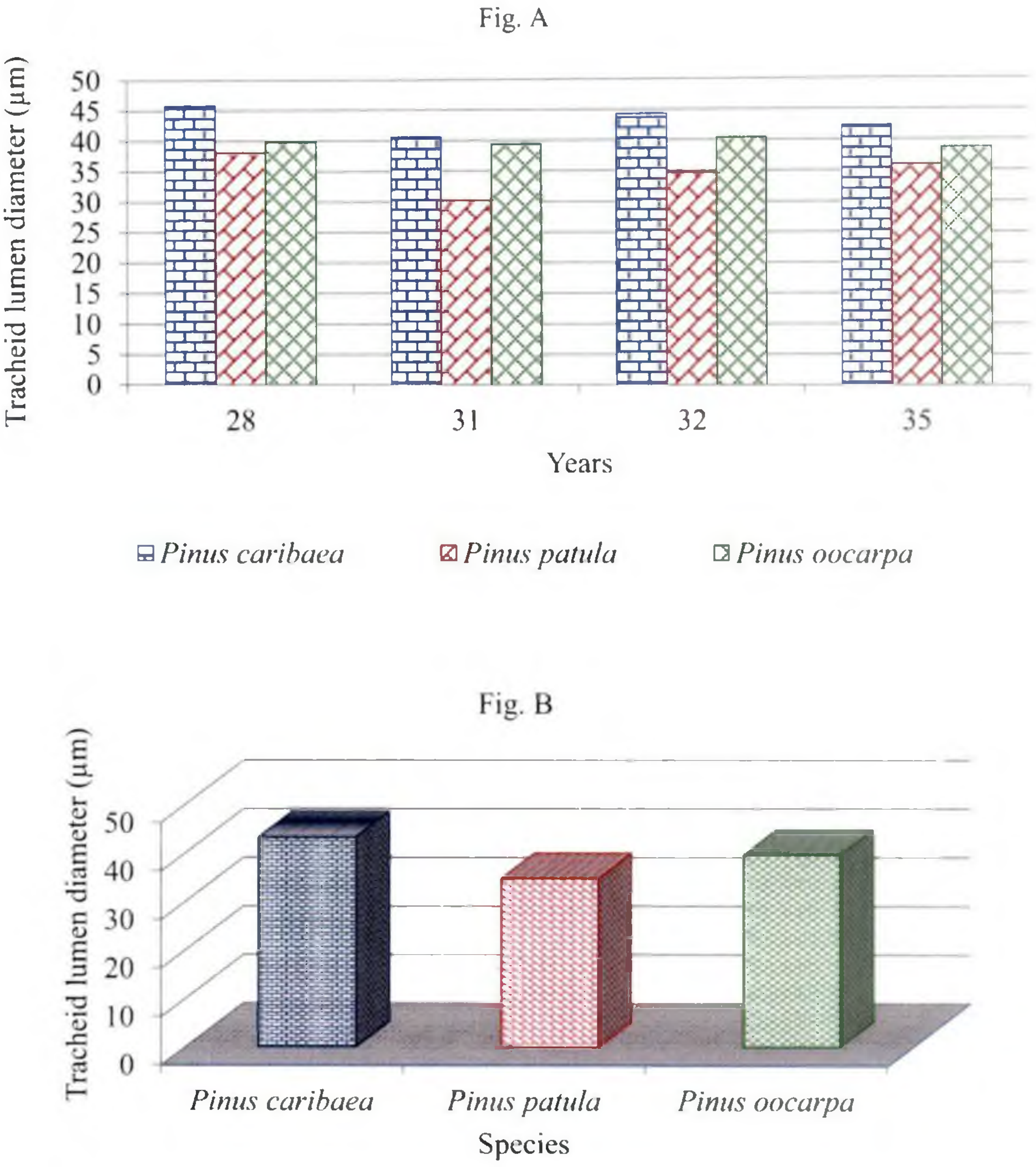

Fig. 21. Variation in tracheid lumen diameter between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

The results showed no significant difference in tracheid lumen diameter at different ages within a species (Table 20). From this it can be seen in *Pinus caribaea* the values ranged from 40.56 µm in 31 years old plantation to 45.74 µm in 28 years old plantation. While *Pinus patula* was found to have higher value in 28 years old plantation (38.13 µm) and lowest in 31 years old plantation (30.20 µm). But *Pinus oocarpa* had values ranging from 38.72 µm (35 years old plantation) to 40.38 µm (32 years old plantation) (Fig. 21A).

The species mean on tracheid lumen diameter averaged over all ages showed significant difference between *Pinus caribaea* (43.23) and *Pinus patula* (34.73), whereas these two species found to be homogenous with *Pinus oocarpa* (39.55) (Fig. 21B).

4.2.1.4b Variation due to position in a species within an age group

The results of tracheid lumen diameter values of the three pine species at each radial position with in an age group is given in Table 21 and illustrated in Figure 22. Results of analysis of variance showed that there is no statistically significant difference between the radial positions in a species within an age group.

In 28 years old plantation the tracheid lumen diameter showed an increase in value from pith (33.75 µm) to periphery (44.63 µm) in *Pinus oocarpa*. However, in the case of *Pinus caribaea* and *Pinus patula*, the radial variation was found to increase from pith to middle from 43.26 µm to 50.40 µm and from 34.78 µm to 40.80 µm respectively. Radial variation in tracheid lumen diameter showed a decrease at the periphery position in both the species (43.56 µm and 38.83 µm). These results are graphically illustrated in Figure 22A.

The tracheid lumen diameter values at each radial position in the 31 years old plantation is presented graphically in Figure 22B. This graph shows that there is a gradual decrease in tracheid lumen diameter from pith to periphery in both

Table 21. Mean tracheid lumen diameter at pith, middle and periphery of pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Tracheid lumen diameter (µm)		
28	*Pinus caribaea*	43.26 (4.94)	50.40 (5.17)	43.56 (7.33)
	Pinus patula	34.78 (7.61)	40.80 (8.70)	38.83 (5.07)
	Pinus oocarpa	33.75 (1.73)	40.93 (5.61)	44.63 (12.11)
31	*Pinus caribaea*	46.47 (1.15)	41.04 (7.25)	34.17 (6.15)
	Pinus patula	32.19 (2.70)	28.62 (5.34)	29.78 (9.22)
	Pinus oocarpa	41.33 (5.55)	40.84 (3.26)	35.87 (15.58)
32	*Pinus caribaea*	38.68 (2.16)	43.21 (5.91)	51.07 (1.96)
	Pinus patula	33.17 (1.33)	33.99 (7.49)	36.81 (3.54)
	Pinus oocarpa	39.55 (0.58)	40.42 (12.32)	41.18 (6.56)
35	*Pinus caribaea*	40.22 (2.20)	43.07 (7.05)	43.58 (17.13)
	Pinus patula	39.58 (3.88)	36.16 (3.21)	31.98 (4.70)
	Pinus oocarpa	40.25 (5.81)	40.35 (3.21)	35.55 (15.52)
F value	1.18^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

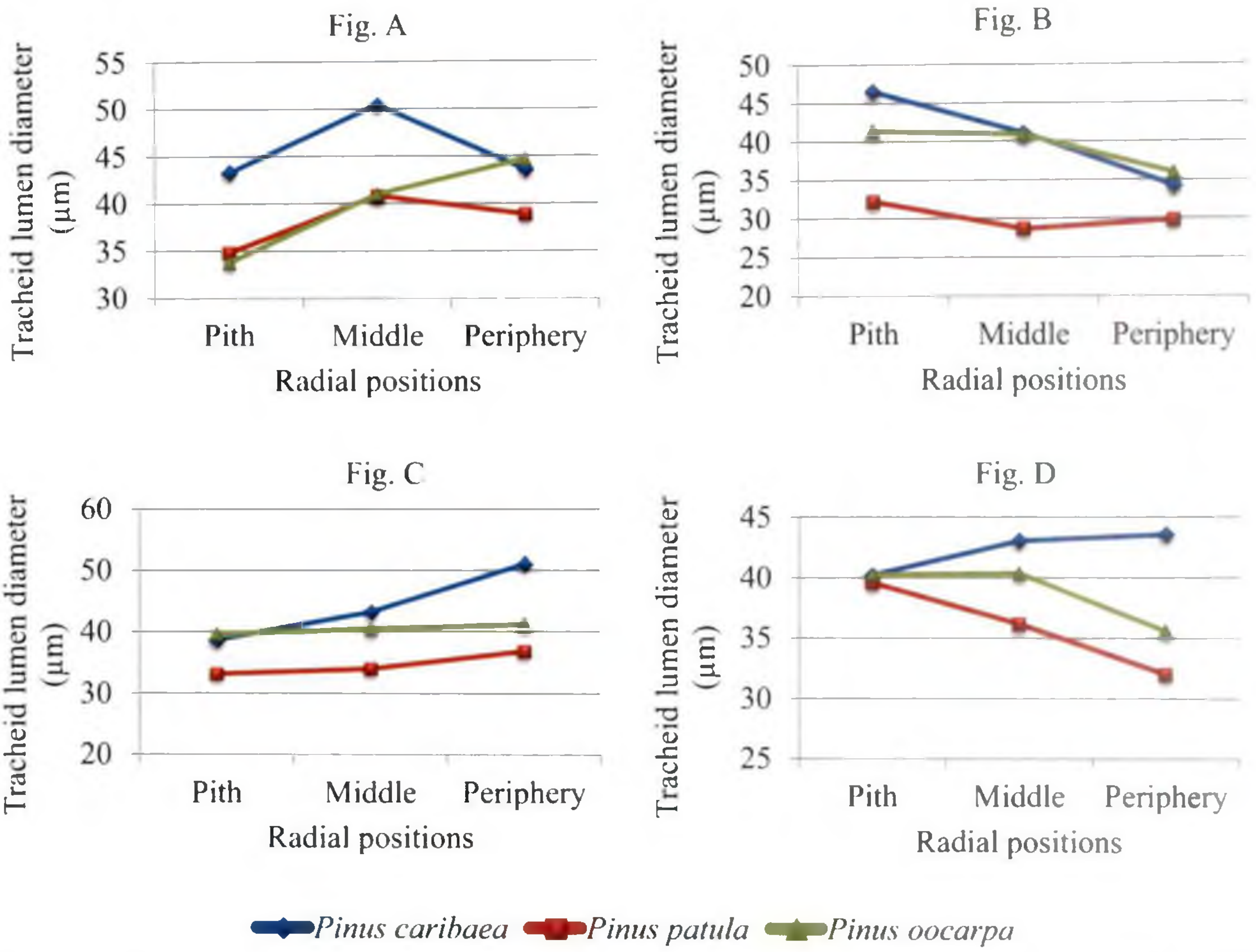

Fig. 22. Radial variation of tracheid lumen diameter in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

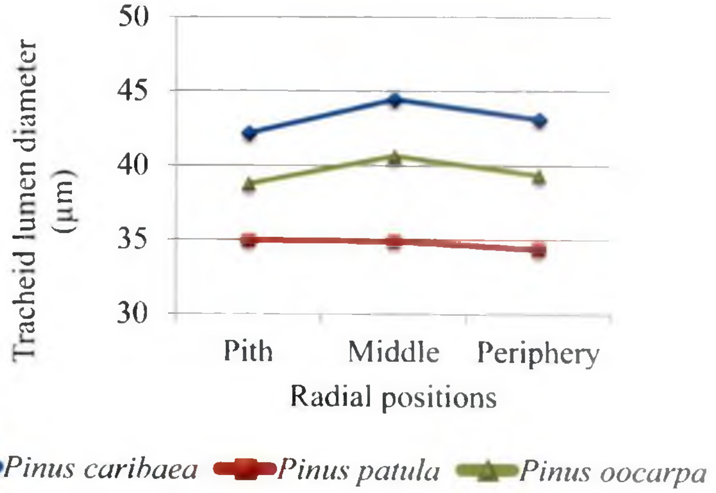

Fig. 23. Radial variation in mean tracheid lumen diameter of pine species averaged over all ages

Pinus caribaea and *Pinus oocarpa* (46.47 µm to 34.17 µm and 41.33 µm to 35.87 µm respectively). But in *Pinus patula*, it was found to have lesser value at middle (28.62 µm) compared to pith (32.19 µm) and then it increased slightly at the periphery position (29.78 µm). Figure 22B also shows that all the three species were having higher tracheid lumen diameter at the pith position.

In 32 years old plantations, tracheid lumen, though showed increasing trend from pith to periphery in all the three pine species, the increase was not statistically significant (Fig. 22C). In *Pinus caribaea* values were found to range from 38.68 µm to 51.07 µm, in *Pinus patula* it ranged from 33.17 µm to 36.81 µm and in *Pinus oocarpa* it was found to range from 39.55 µm to 41.18 µm.

From Figure 22D, it can be seen that tracheid lumen diameter decreased from pith (39.58 µm) to periphery (31.98 µm) in *Pinus patula* that belonged to 35 years old plantation. However, *Pinus caribaea* had an increase in value from pith (40.22 µm) to periphery (43.58 µm), while in *Pinus oocarpa* this was found to increase from pith (40.25 µm) to middle (40.35 µm) and then decrease at the periphery position (35.55 µm).

4.2.1.4c Variation due to position within species averaged across all ages

Results showed no significant variation in tracheid lumen diameter with respect to position within each species averaged across all ages. Species mean averaged across all the ages in different radial positions are presented in Table 22 and Figure 23.

From Table 22 it can be seen that tracheid lumen diameter values were found to show an increasing trend from pith to middle position in *Pinus caribaea* (42.16 µm to 44.43 µm) and *Pinus oocarpa* (38.72 µm to 40.63 µm). In both these species, the values at the radial positions were found to decrease at periphery compared to middle position i.e. 43.10 µm and 39.31 µm respectively. However, in *Pinus patula* tracheid lumen diameter was found to have a small decrease in value from pith (34.93 µm) to periphery (34.35 µm).

Table 22. Mean tracheid lumen diameter of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Tracheid lumen diameter (µm)		
Pith	42.16 (4.02)	34.93 (4.87)	38.72 (4.66)
Middle	44.43 (6.60)	34.89 (7.20)	40.63 (6.10)
Periphery	43.10 (10.48)	34.35 (6.39)	39.31 (11.75)
F value	0.20^{ns} (for comparing between position within a species)		

ns - non significant; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.2.1.5 Runkel ratio

4.2.1.5a Variation due to age and species

The data on variation in Runkel ratio with respect to age and species is presented in Table 23 and Figure 24. Results revealed that age and species interactions were not significant. Hence, the effect of age is not varying with species with in an age and between different ages within a species. Species variation across all ages was also found to be non significant among the three pine species.

Runkel ratio among species was found to range in the 28 years old plantation from 0.23 (*Pinus caribaea*) to 0.25 (*Pinus oocarpa*). In the 31 years old plantation it ranged from 0.15 (*Pinus patula*) to 0.50 (*Pinus oocarpa*), in the 32 years old plantation it ranged from 0.20 (*Pinus caribaea*) to 0.32 (*Pinus oocarpa*) and in 35 years old plantation it ranged from 0.35 (*Pinus caribaea*) to 0.40 (*Pinus oocarpa* and *Pinus patula*). These results regarding Runkel ratio among species in different ages are presented graphically in Figure 24A.

From Figure 24A, it can be seen that the Runkel ratio was found to range in *Pinus caribaea* from 0.20 (32 years old plantation) to 0.35 (35 years old plantation), in *Pinus patula* it ranged from 0.15 (31 years old plantation) to 0.40 (35 years old plantation) and in *Pinus oocarpa* it ranged from 0.25 (28 years old plantation) to 0.50 (31 years old plantation).

Table 23. Mean Runkel ratio of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Runkel ratio				
Pinus caribaea	0.23 (0.09)	0.29 (0.16)	0.20 (0.06)	0.35 (0.25)	0.27 (0.16)
Pinus patula	0.24 (0.09)	0.15 (0.27)	0.27 (0.15)	0.40 (0.31)	0.33 (0.23)
Pinus oocarpa	0.25 (0.08)	0.50 (0.58)	0.32 (0.16)	0.40 (0.43)	0.37 (0.37)
F value	0.29^{ns} (for comparing between age and species) 1.51^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

Species mean, averaged over all ages was found to have no significant difference between the three pine species that were studied. These results are presented in Table 23 and Figure 24B. From this, it can be found that *Pinus caribaea*

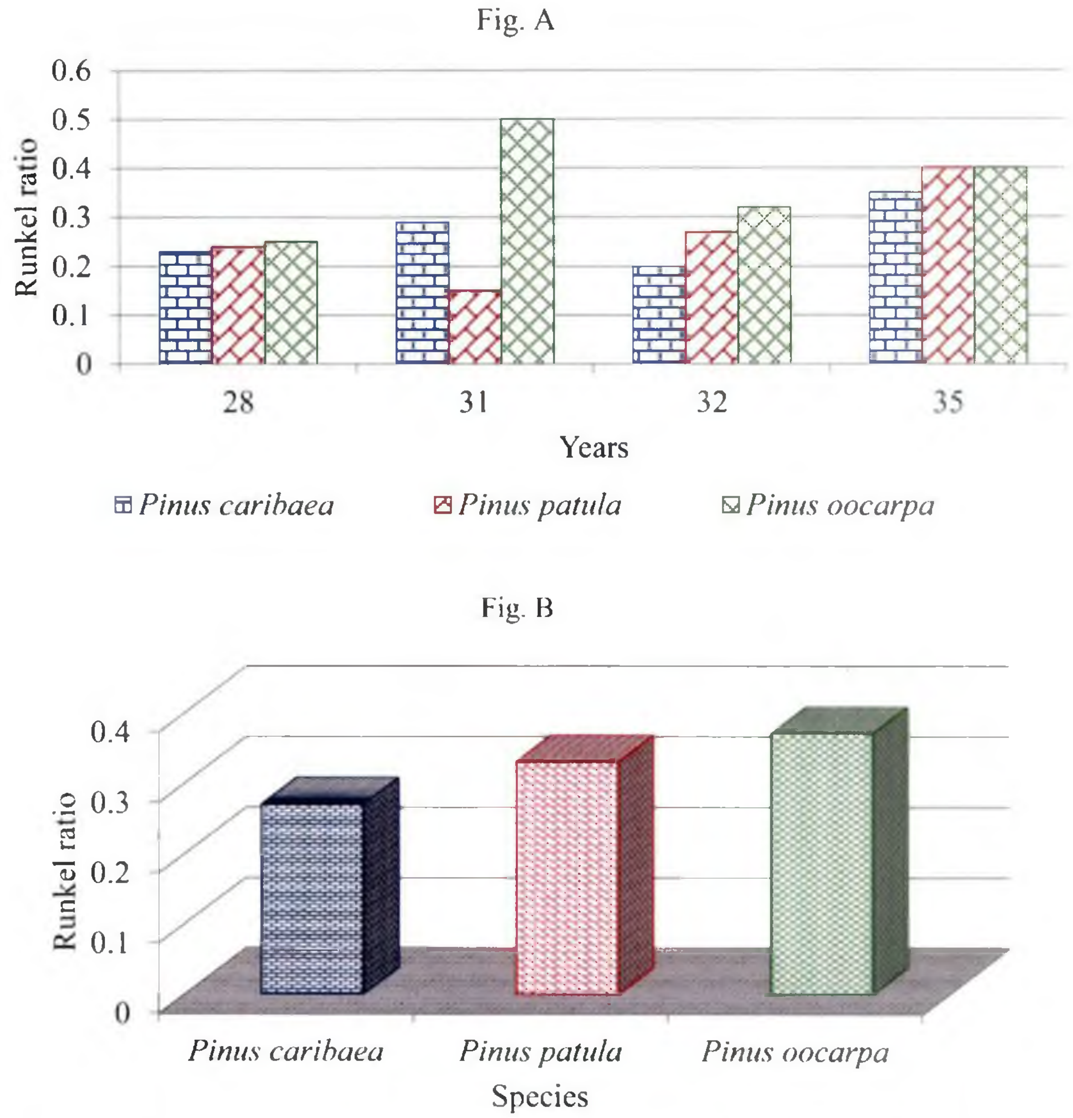

Fig. 24. Variation in Runkel ratio between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

(0.27) had the lowest value and *Pinus oocarpa* (0.37) had the highest value for Runkel ratio. On the other hand, *Pinus patula* (0.33) had only moderate value.

4.2.1.5b Variation due to position in a species within an age group

Analysis of variance showed no significant difference in Runkel ratio due to the interactions between age and position within species. The summarized results are presented in Table 24 and Figure 25.

The values showed an increasing trend in *Pinus caribaea* from pith (0.18) to periphery position (0.32) in 28 years old plantation (Fig.25A). But in *Pinus patula*, both pith and middle position had similar values (0.20) for Runkel ratio. It was then found to increase at the periphery position (0.33), whereas in *Pinus oocarpa* this first decreased from pith (0.24) to middle (0.23) and then increased at the periphery (0.27) position.

From Figure 25B, it can be seen that the Runkel ratio of 31 years old plantation was found to increase from pith to periphery position in all the three pine species. In *Pinus caribaea* it ranged from 0.21 to 0.41, in *Pinus patula* it ranged from 0.12 to 0.57 and in *Pinus oocarpa* it ranged from 0.25 to 0.92.

In the 32 years old plantation, the Runkel ratio was found to increase from pith to middle in *Pinus caribea* and *Pinus patula* i.e. 0.14 to 0.25 and 0.15 to 0.34 respectively. In both these species, there was an increase in values at periphery as compared to middle position (0.22 and 0.31 respectively) (Fig. 25C). On the other hand, *Pinus oocarpa* had values that ranged from 0.20 (pith) to 0.38 (periphery).

The radial variation in all the three pine species showed an in crease in Runkel ratio from pith to periphery position in 35 years old plantation (Fig. 25D). *Pinus caribaea* was found to have values ranging from 0.28 to 0.51 and *Pinus patula*

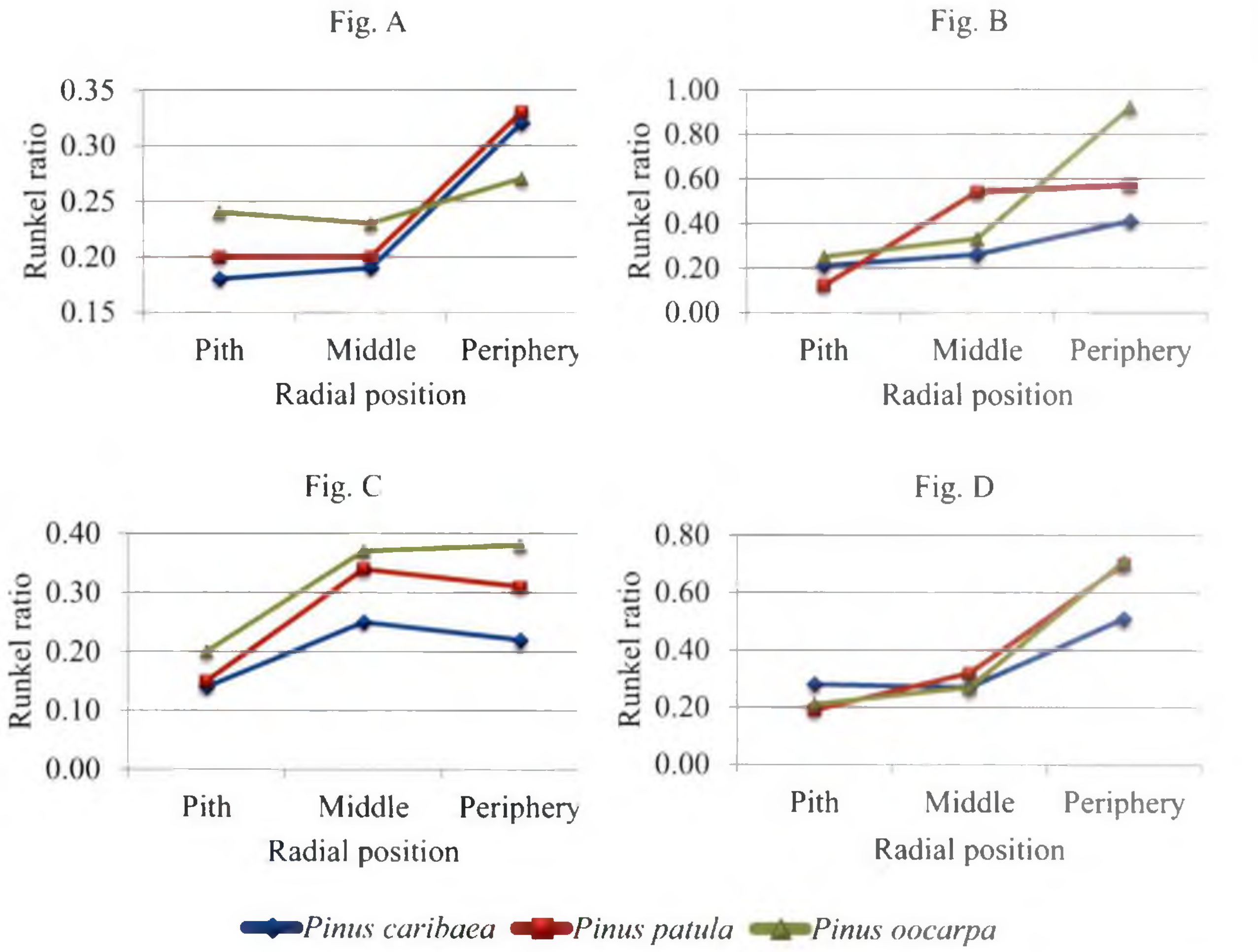

Fig. 25. Radial variation of Runkel ratio in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

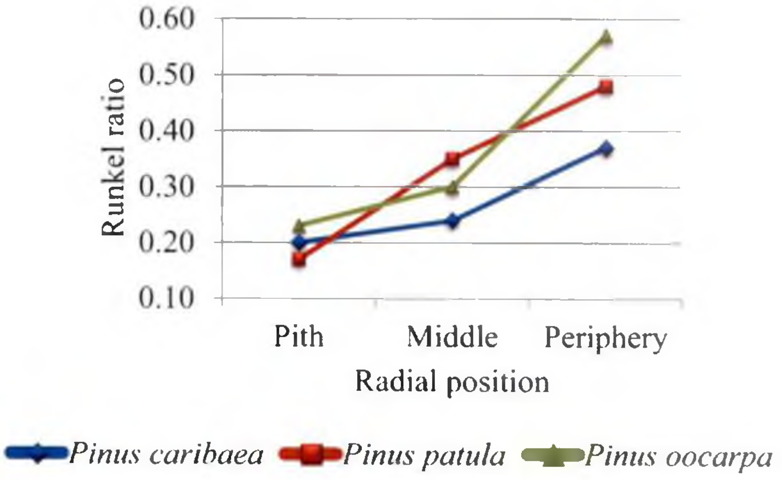

Fig. 26. Radial variation in mean Runkel ratio of pine species averaged over all ages

Table 24. Mean Runkel ratio at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Runkel ratio		
28	*Pinus caribaea*	0.18 (0.04)	0.19 (0.07)	0.32 (0.07)
	Pinus patula	0.20 (0.05)	0.20 (0.06)	0.33 (0.07)
	Pinus oocarpa	0.24 (0.03)	0.23 (0.08)	0.27 (0.13)
31	*Pinus caribaea*	0.21 (0.06)	0.26 (0.06)	0.41 (0.24)
	Pinus patula	0.12 (0.02)	0.54 (0.31)	0.57 (0.13)
	Pinus oocarpa	0.25 (0.07)	0.33 (0.11)	0.92 (0.96)
32	*Pinus caribaea*	0.14 (0.04)	0.25 (0.06)	0.22 (0.03)
	Pinus patula	0.15 (0.05)	0.34 (0.23)	0.31 (0.04)
	Pinus oocarpa	0.20 (0.05)	0.37 (0.24)	0.38 (0.12)
35	*Pinus caribaea*	0.28 (0.05)	0.27 (0.12)	0.51 (0.43)
	Pinus patula	0.19 (0.10)	0.32 (0.24)	0.70 (0.33)
	Pinus oocarpa	0.21 (0.05)	0.27 (0.09)	0.71 (0.72)
F value	0.76^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

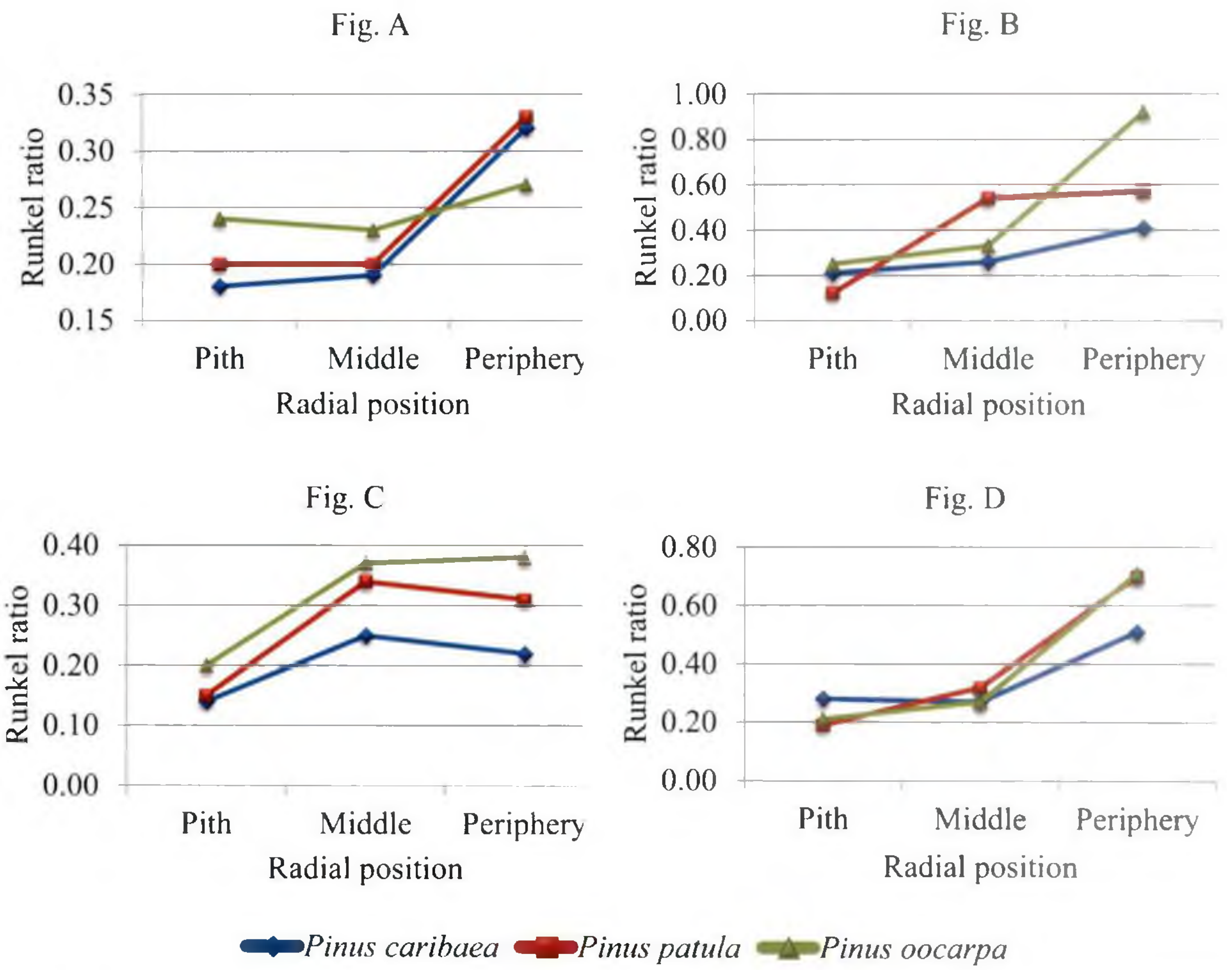

Fig. 25. Radial variation of Runkel ratio in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

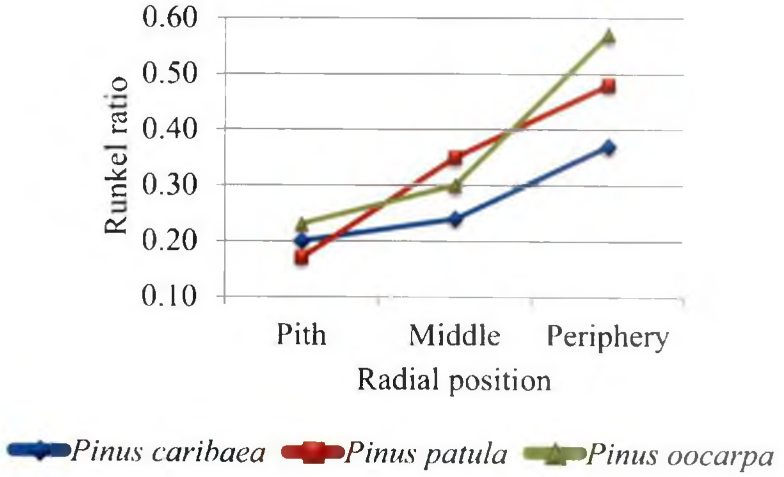

Fig. 26. Radial variation in mean Runkel ratio of pine species averaged over all ages

had values that ranged from 0.19 to 0.70. It can also be seen that in *Pinus oocarpa* values ranged from 0.21 to 0.71.

4.2.1.5c Variation due to position within species averaged across all ages

The summarized data on Runkel ratio at the radial positions of three species across all ages are presented in Table 25 and Figure 26. Analysis of variance revealed that this variation between species is highly significant at 1 per cent level and age did not have any influence on this variation (Table 24).

Table 25. Mean Runkel ratio of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Runkel ratio		
Pith	0.20^{a} (0.07)	0.17^{b} (0.06)	0.23^{b} (0.05)
Middle	0.24^{a} (0.08)	0.35^{a} (0.23)	0.30^{ab} (0.14)
Periphery	0.37^{a} (0.24)	0.48^{a} (0.23)	0.57^{a} (0.58)
F value	4.02** (for comparing between position within a species)		
C.D	0.277		

** Significant at 1 % level; C.D – critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

From Figure 26, it can be seen that there is an increasing pattern in Runkel ratio from pith to periphery position in all the three species. In *Pinus caribea* there was no significant difference in Runkel ratio at radial positions and it varied from 0.20 to 0.37. But in *Pinus patula*, pith (0.17) differed significantly from the middle

(0.35) and periphery positions (0.48) and the latter two radial positions were found to be homogenous. In *Pinus oocarpa*, pith (0.23) differed significantly from periphery (0.57) position, while the middle (0.30) position was found to be homogenous at both pith and periphery.

4.2.1.6 Shape factor

4.2.1.6a Variation due to age and species

Results showed that the interactions between age and species are not significant with respect to shape factor. Also, the species mean across ages was found to have no significant variation among the three pine species that were studied. These results are presented in Table 26 and Figure 27.

Table 26. Mean shape factor of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Shape factor				
Pinus caribaea	0.20 (0.06)	0.25 (0.12)	0.18 (0.05)	0.26 (0.13)	0.22 (0.09)
Pinus patula	0.21 (0.06)	0.29 (0.16)	0.22 (0.09)	0.29 (0.17)	0.25 (0.13)
Pinus oocarpa	0.21 (0.06)	0.30 (0.16)	0.25 (0.10)	0.26 (0.16)	0.26 (0.13)
F value	0.30^{ns} (for comparing between age and species) 1.17^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

The results regarding shape factor among species within different ages are illustrated graphically in Figure 27A. From this, it can be seen that in the 28 years old plantation, shape factor was found to range from 0.20 (*Pinus caribaea*) to 0.21

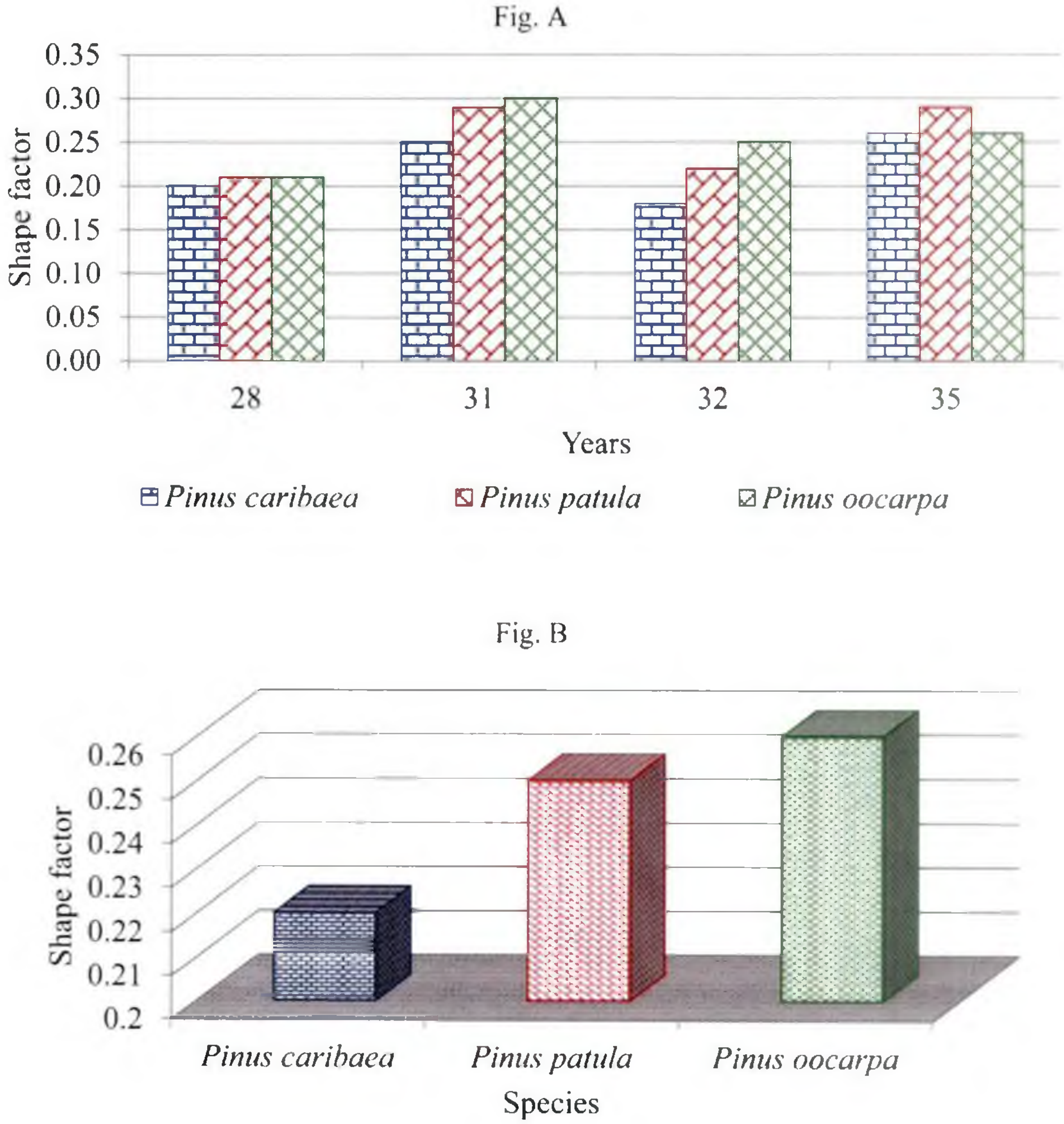

Fig. 27. Variation in shape factor between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

(*Pinus patula* and *Pinus oocarpa*). In the 31 years old plantation, it ranged from 0.25 (*Pinus caribaea*) to 0.30 (*Pinus oocarpa*); in the 32 years old plantation it ranged from 0.18 (*Pinus caribaea*) to 0.25 (*Pinus oocarpa*) and in the 35 years old plantation it ranged from 0.26 (*Pinus caribaea* and *Pinus oocarpa*) to 0.29 (*Pinus patula*).

In *Pinus caribaea*, the values of shape factor was found to range from 0.18 (32 years old plantation) to 0.26 (35 years old plantation). On the other hand in *Pinus patula* it was found to range from 0.21 (28 years old plantation) to 0.29 (31 and 35 years old plantations). The values ranged from 0.21 (28 years old plantation) to 0.30 (31 years old plantation) in *Pinus oocarpa*. The results related to shape factor is illustrated graphically in Figure 27A.

The species mean averaged over all ages also showed no significant difference among species (Table 26 and Fig. 27B). *Pinus caribaea* had the lowest value (0.22) and *Pinus oocarpa* had the highest value (0.26). But *Pinus patula* (0.25) was found to have moderate value, for shape factor.

4.2.1.6b Variation due to position in a species within an age group

Results pertaining to variation in shape factor between positions in a species within an age group is summarized in Table 27 and Figure 28. Analysis of variance showed no significant difference between radial positions between species within an age group.

In 28 years old plantation, *Pinus caribaea* had an increase in shape factor from pith to periphery position i.e. 0.16 to 0.26. However, in the case of *Pinus patula* both pith and middle positions were found have similar values (0.18) and this value increased at the periphery position (0.27). While in *Pinus oocarpa* the radial variation in shape factor was found to decrease from pith (0.21) to middle (0.20)

Table 27. Mean shape factor at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Shape factor		
28	*Pinus caribaea*	0.16 (0.04)	0.17 (0.06)	0.26 (0.04)
	Pinus patula	0.18 (0.04)	0.18 (0.05)	0.27 (0.05)
	Pinus oocarpa	0.21 (0.02)	0.20 (0.06)	0.23 (0.09)
31	*Pinus caribaea*	0.19 (0.04)	0.22 (0.04)	0.35 (0.17)
	Pinus patula	0.11 (0.01)	0.37 (0.15)	0.40 (0.07)
	Pinus oocarpa	0.22 (0.06)	0.26 (0.07)	0.41 (0.25)
32	*Pinus caribaea*	0.13 (0.04)	0.21 (0.04)	0.19 (0.02)
	Pinus patula	0.14 (0.05)	0.26 (0.14)	0.25 (0.03)
	Pinus oocarpa	0.18 (0.04)	0.28 (0.14)	0.30 (0.08)
35	*Pinus caribaea*	0.24 (0.04)	0.22 (0.08)	0.33 (0.21)
	Pinus patula	0.17 (0.07)	0.25 (0.16)	0.45 (0.15)
	Pinus oocarpa	0.19 (0.04)	0.22 (0.06)	0.38 (0.26)
F value	0.80^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

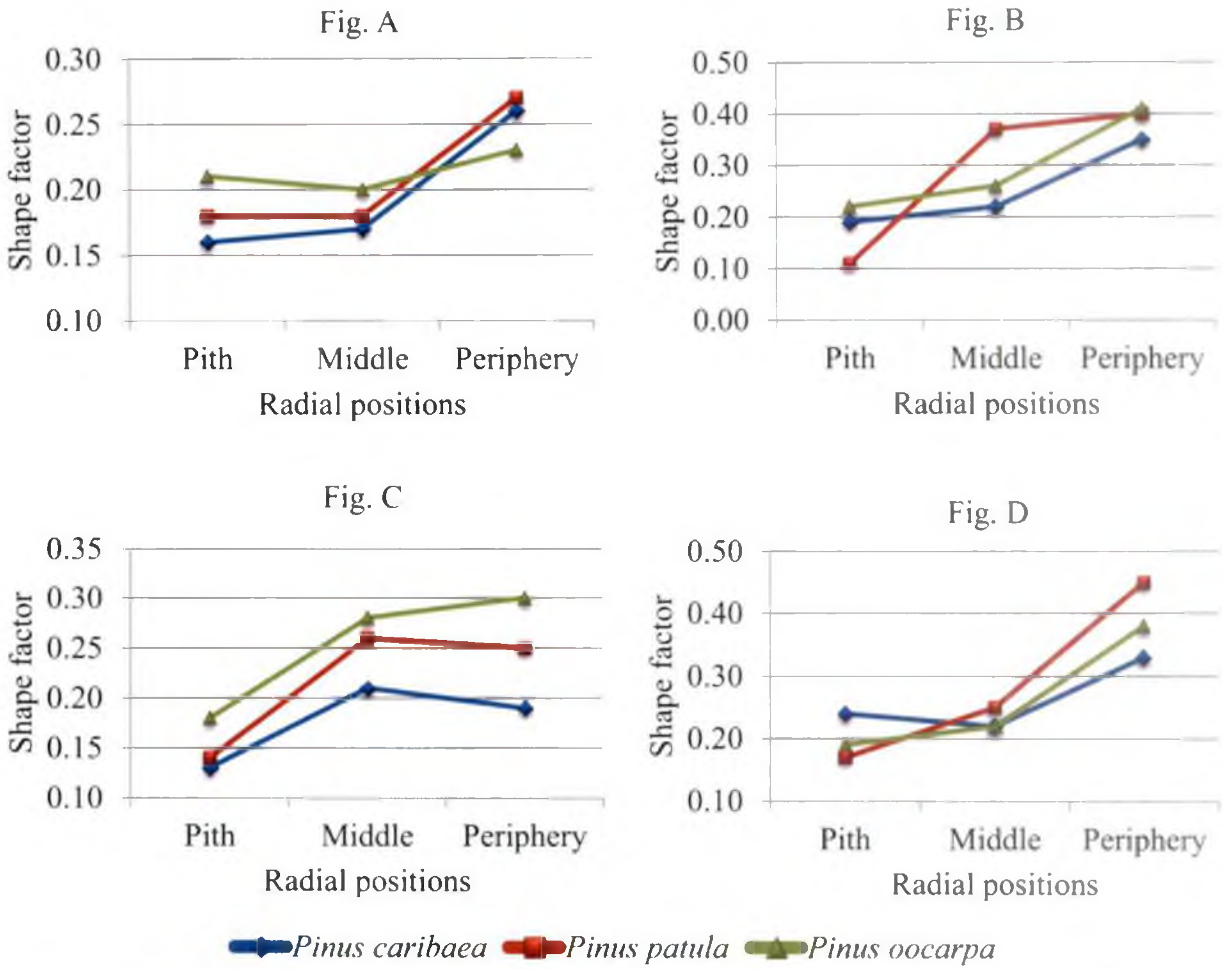

Fig. 28. Radial variation of shape factor in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

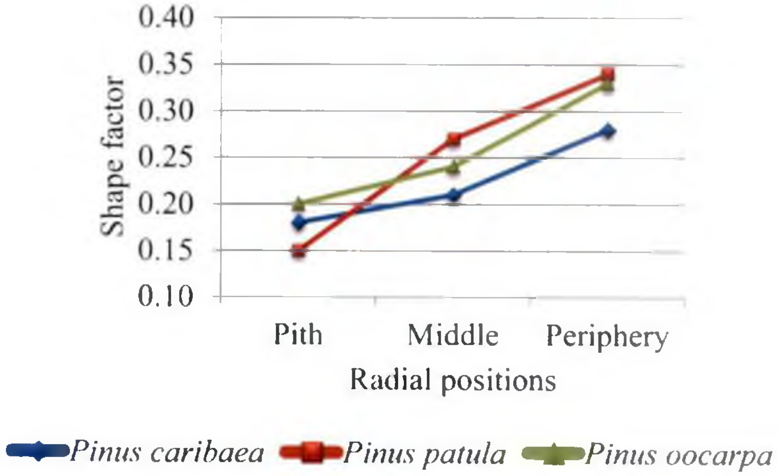

Fig. 29. Radial variation in mean shape factor of pine species averaged over all ages

position and then it increased at the periphery (0.23) position. These results are illustrated in Figure 28A.

Shape factor at each radial positions of three pine species belonging to 31 years old plantation is illustrated in Figure 28B. From this, it can be found out that in all the three pine species, radial variation was found to increase from pith to periphery. *Pinus caribaea* had values ranging from 0.19 to 0.35. In *Pinus patula*, values ranged from 0.11 to 0.40 and in *Pinus oocarpa* it ranged from 0.22 to 0.41.

The results of shape factor values at each radial position of three pine species belonging to 32 years old plantation is graphically illustrated in Figure 28C. From this, it can found out that in both *Pinus caribaea* and *Pinus patula* the shape factor was found to increase from pith to middle i.e. 0.13 to 0.21 and 0.14 to 0.26 respectively. These values were found to decrease at periphery in both the species (0.19 and 0.25 respectively). On the other hand, *Pinus oocarpa* was found to have an increase in shape factor from pith (0.18) to periphery (0.30).

Radial positions in 35 years old plantation species showed an increase in shape factor from pith to periphery positions in *Pinus patula* (0.17 to 0.45) and *Pinus oocarpa* (0.19 to 0.38) (Fig. 28D). However, *Pinus caribaea* had values such as 0.24 at pith, 0.22 at middle and 0.33 at periphery position.

4.2.1.6c Variation due to position within species averaged across all ages

The variation in radial positions of three pine species across all ages with respect to shape factor was found to differ significantly at 1 per cent variance level and these results are presented in Table 28 and Figure 29.

From Table 28, it can be seen that all the three species showed increase in specific gravity from pith to periphery position and this variation is not influenced by age (Table 27). There was no significant radial variation in *Pinus caribaea* and the values varied from 0.18 to 0.28, while in *Pinus patula* the pith position (0.15) was found to have significant difference from the periphery (0.34) and these two radial positions were found to be at par with middle value (0.27). Similar variation was seen in *Pinus oocarpa* in which the middle position (0.24) was found to be homogenous with pith (0.20) and periphery (0.33), and the latter two were found to differ significantly with each other.

Table 28. Mean shape factor of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Shape factor		
Pith	0.18^{a} (0.05)	0.15^{b} (0.05)	0.20^{b} (0.04)
Middle	0.21^{a} (0.05)	0.27^{ab} (0.13)	0.24^{ab} (0.08)
Periphery	0.28^{a} (0.14)	0.34^{a} (0.11)	0.33^{a} (0.18)
F value	6.08** (for comparing between position within a species)		
C.D	0.109		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.2.1.7 Slenderness ratio

4.2.1.7a Variation due to age and species

Results of analysis of variance showed that the interactions between age and species were not significant. This indicates that the effect of age is not varying with species. However, comparison of age means of the same species or between species means at the same age level was carried out and results are presented in Table 29 and Figure 30.

Table 29. Mean slenderness ratio of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Slenderness ratio				
Pinus caribaea	76.70 (12.97)	70.67 (10.98)	85.39 (13.12)	76.21 (20.99)	77.24^{b} (15.32)
Pinus patula	94.03 (12.15)	96.81 (30.05)	95.21 (14.49)	69.09 (18.29)	88.79^{a} (22.33)
Pinus oocarpa	79.36 (20.45)	79.73 (13.67)	86.04 (9.41)	78.70 (15.28)	80.96^{ab} (14.86)
F value	1.60^{ns} (for comparing between age and species) 3.73* (for comparing species averaged over all ages)				
C.D	8.90				

* Significant at 5 % level; ns - non significant; C.D - critical difference; values within parentheses is standard deviation

From Figure 30A, it can be seen that slenderness ratio was found to range in the 28 years old plantation from 76.70 (*Pinus caribaea*) to 94.03 (*Pinus patula*); in the 31 years old plantation it ranged from 70.67 (*Pinus caribaea*) to 96.81 (*Pinus patula*); in the 32 years old plantation it ranged from 85.39 (*Pinus caribaea*) to 95.21 (*Pinus patula*) and in the 35 years old plantation it ranged from 69.09 (*Pinus patula*) to 78.70 (*Pinus oocarpa*).

Table 29 also shows the slenderness ratios in each of the three pine species at different age levels. This comparison shows that *Pinus caribaea* had values ranging from 70.67 (31 years old plantation) to 85.39 (32 years old plantation) and in *Pinus patula* it ranged from 69.09 (35 years old plantation) to 96.81 (31 years old

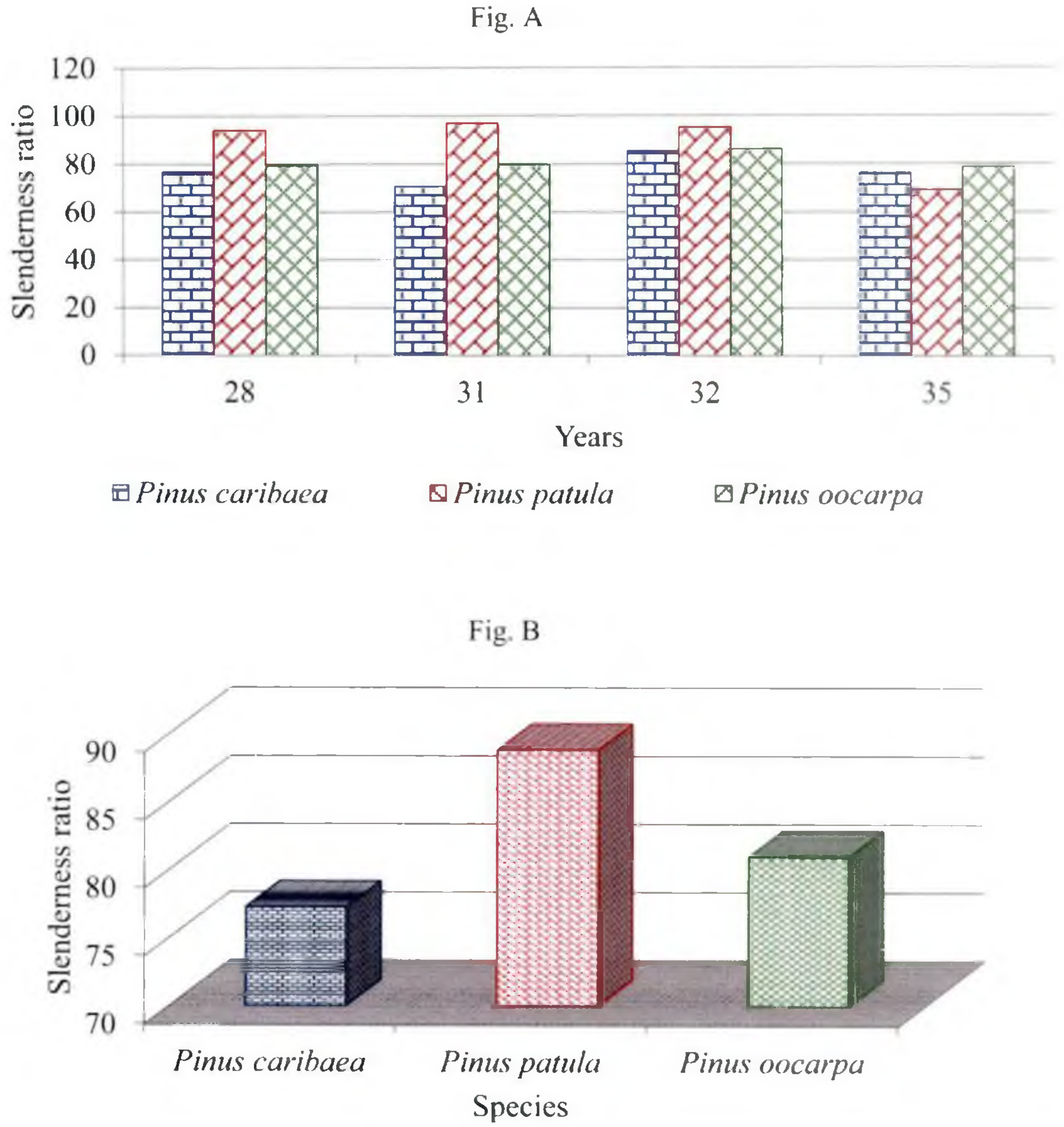

Fig. 30. Variation in slenderness ratio between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

plantation), while in *Pinus oocarpa*, slenderness ratio was found to range from 78.70 (35 years old plantation) to 86.04 (32 years old plantation) (Fig. 30A).

The species mean averaged across all ages also showed significant difference in slenderness ratio between the three pine species (5% level). From Table 29, it can be found out that *Pinus caribaea* (77.24) differed significantly from *Pinus patula* (88.79), whereas *Pinus oocarpa* (80.96) had values which are homogenous with the other two pine species (Fig. 30B).

4.2.1.7b Variation due to position in a species within an age group

The variation in slenderness ratio due to radial positions in a species within in an age group was found to have no significant difference. The comparison between positions within each species for each age level taking the mean values was done and the results are given in Table 30 and presented graphically in Figure 31.

Radially, slenderness ratio had an increase in values from pith to periphery in *Pinus patula* and *Pinus oocarpa* which belonging to 28 years old plantation. On the other hand in *Pinus caribaea* it was found to increase from pith to middle and then decreased at periphery. This radial variation is illustrated in Figure 31A. In *Pinus caribaea*, slenderness ratio was found to range from 65.42 to 84.74; in *Pinus patula* it ranged from 79.43 to 102.2 and in *Pinus oocarpa* it ranged from 59.64 to 89.37.

Figure 31B indicates that all the three species showed an increase in slenderness ratio values from pith to periphery (31 years old plantation). In *Pinus caribaea*, the slenderness ratio values were found to range from 63.22 to 78.83, in *Pinus patula* it ranged from 74.80 to 113.77 and in *Pinus oocarpa* it ranged from 74.39 to 83.50.

Table 30. Mean slenderness ratio at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Slenderness ratio		
28	*Pinus caribaea*	65.42 (9.40)	84.74 (13.99)	79.93 (9.25)
	Pinus patula	79.43 (2.75)	100.47 (9.47)	102.2 (3.35)
	Pinus oocarpa	59.64 (3.87)	89.07 (10.46)	89.37 (25.95)
31	*Pinus caribaea*	63.22 (10.91)	69.97 (12.83)	78.83 (3.80)
	Pinus patula	74.80 (5.03)	101.85 (36.28)	113.77 (32.77)
	Pinus oocarpa	74.39 (11.64)	81.31 (0.71)	83.50 (23.31)
32	*Pinus caribaea*	71.87 (7.41)	91.27 (13.13)	93.02 (6.91)
	Pinus patula	83.21 (4.75)	95.88 (11.92)	106.56 (16.27)
	Pinus oocarpa	82.78 (13.10)	87.71 (11.48)	87.63 (5.19)
35	*Pinus caribaea*	82.57 (4.74)	62.79 (10.03)	83.27 (35.12)
	Pinus patula	68.88 (23.45)	55.97 (15.16)	82.44 (5.68)
	Pinus oocarpa	72.79 (13.66)	80.44 (3.15)	82.87 (25.58)
F value	1.12^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

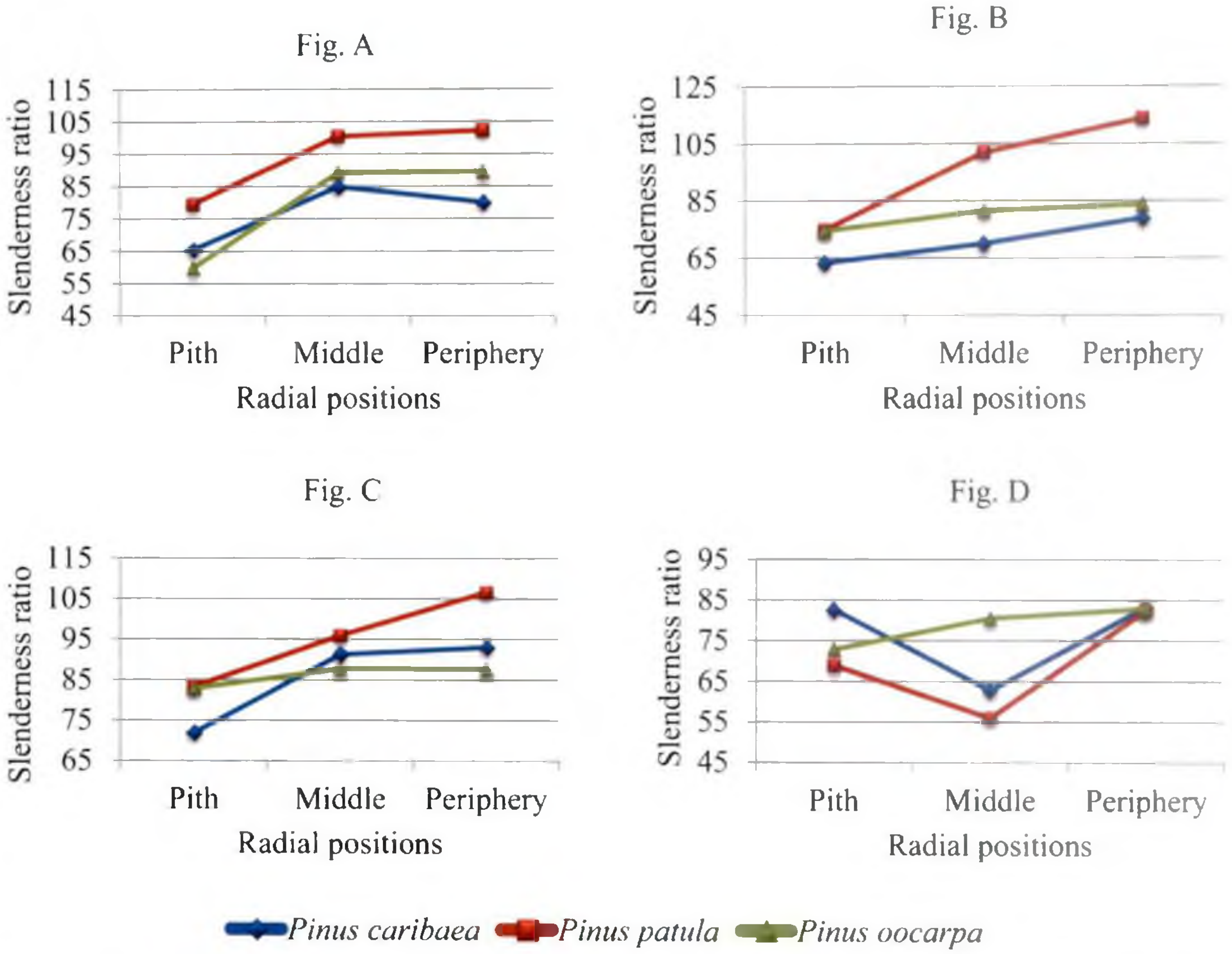

Fig. 31. Radial variation of slenderness ratio in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

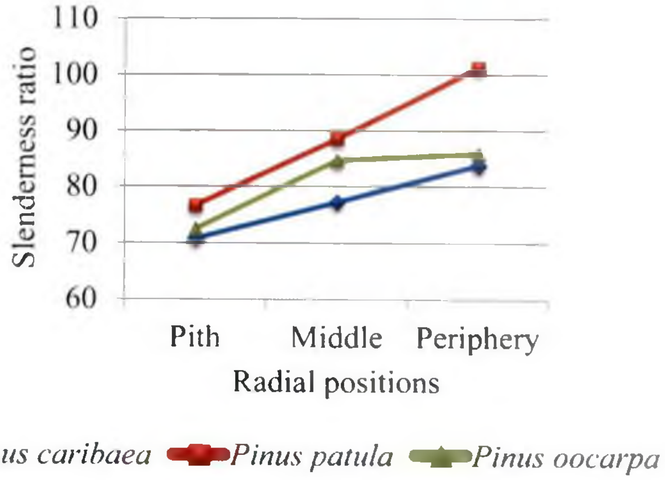

Fig. 32. Radial variation in mean slenderness ratio of pine species averaged over all ages

The comparison between radial positions within species belonging to 32 years old plantation is illustrated in Figure 31C. This comparison shows that radial positions showed an increase in slenderness value from pith to periphery in *Pinus caribaea* (71.87 to 93.02) and *Pinus patula* (83.21 to 106.56). But in *Pinus oocarpa*, middle (87.71) position had higher values than pith (82.78) and periphery (87.63).

Radial variations in the three pines which were 35 years old are presented graphically in Figure 31D. It can be seen that slenderness ratio was found to increase from pith to periphery position in *Pinus oocarpa* (72.79 to 82.87). In the case of *Pinus caribaea*, the value was found to decrease from pith (82.57) to middle (62.79) and then increased at the periphery (83.27) position. Similarly, in *Pinus patula*, slenderness ratio values ranged from 68.88 at pith, 55.97 at middle and 82.44 at periphery position.

4.2.1.7c Variation due to position within species averaged across all ages

The mean slenderness ratio of three pine species at different radial positions averaged over all ages was found have highly significant difference at 1 percent variance level. These results are presented in Table 31.

The graphical illustration regarding variation in slenderness ratio shows that in all three species, the radial variation was found to have an increasing trend from pith to periphery position (Fig. 32). *Pinus caribaea* had no significant difference between radial positions and the values varied from 70.77 to 83.76. Similarly, *Pinus oocarpa* also had no significant differences among the radial positions and the values were found to vary from 72.40 to 85.84. But, in the case of *Pinus patula,* pith (76.58) differed significantly from periphery (101.24), whereas the middle (88.54) position was found to be homogenous with other two radial positions with respect to slenderness ratio.

Table 31. Mean slenderness ratio of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Slenderness ratio		
Pith	70.77^{a} (10.65)	76.58^{b} (11.89)	72.40^{a} (12.94)
Middle	77.19^{a} (15.99)	88.54^{ab} (26.73)	84.63^{a} (7.84)
Periphery	83.76^{a} (16.89)	101.24^{a} (19.96)	85.84^{a} (18.80)
F value	5.10** (for comparing between position within a species)		
C.D	15.30		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.2.1.8 Coefficient of flexibility

4.2.1.8a Variation due to age and species

The data on variation in coefficient of flexibility with respect to age and species is presented in Table 32 and Figure 33. Analysis of variance conducted revealed that age and species interactions were not significant. Hence, the effect of age is not varying with species within an age and between different ages within a species.

Coefficient of flexibility among species belonging to 28 years old plantation was found to have values ranging from 80.86 (*Pinus oocarpa*) to 82.03

(*Pinus caribaea*). In the 31 years old plantation it ranged from 73.92 (*Pinus oocarpa*) to 78.62 (*Pinus caribaea*); in the 32 years old plantation it ranged from 77.63 (*Pinus oocarpa*) to 83.88 (*Pinus caribaea*) and in 35 years old plantation it ranged from 74.80 (*Pinus patula*) to 76.64 (*Pinus oocarpa*). These results regarding coefficient of flexibility among species at different ages are illustrated in Figure 33A.

From Figure 33A it can also be seen that in *Pinus caribaea* the coefficient of flexibility was found to range from 76.61 (35 years old plantation) to 83.88 (32 years old plantation), in *Pinus patula* it ranged from 74.43 (31 years old plantation) to 81.21 (28 years old plantation) and in *Pinus oocarpa* it ranged from 73.92 (31 years old plantation) to 80.86 (28 years old plantation).

Table 32. Mean coefficient of flexibility of pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Coefficient of flexibility				
Pinus caribaea	82.03 (5.25)	78.62 (7.67)	83.88 (4.19)	76.61 (10.20)	80.28 (7.47)
Pinus patula	81.21 (5.29)	74.43 (13.23)	80.46 (7.73)	74.80 (13.70)	77.73 (10.63)
Pinus oocarpa	80.86 (4.74)	73.92 (13.25)	77.63 (8.19)	76.64 (12.89)	77.26 (10.24)
F value	0.36^{ns} (for comparing between age and species) 1.55^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

Species mean, averaged over all ages was also found to have no significant difference and the mean values of coefficient of flexibility are presented in Table 32. Among the three species *Pinus caribaea* (80.28) had higher values for coefficient of

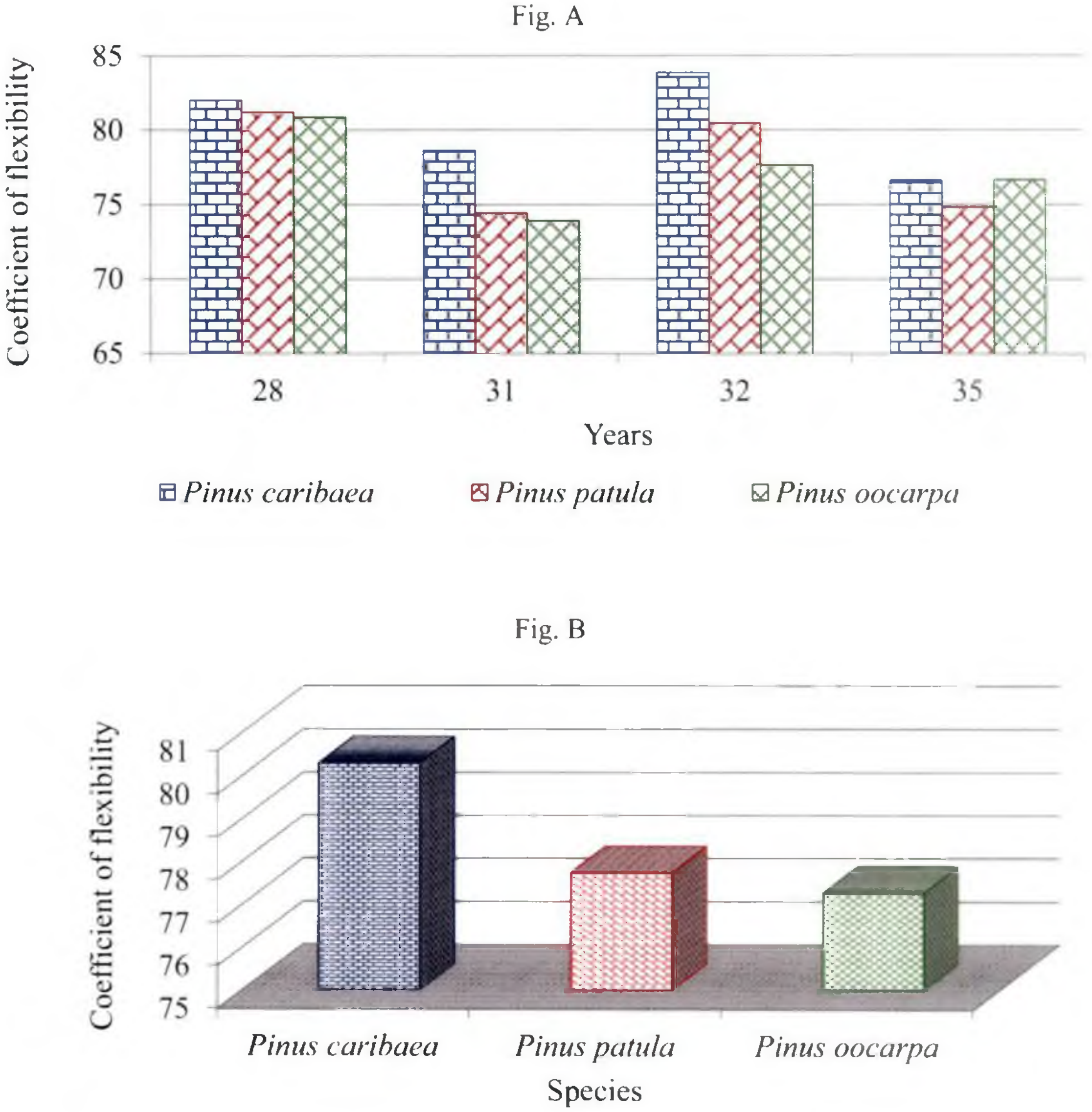

Fig. 33. Variation in coefficient of flexibility between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

flexibility and *Pinus oocarpa* (77.26) had the lowest value of it, whereas *Pinus patula* (77.73) was found to have moderate values for coefficient of flexibility (Fig. 33B).

4.2.1.8b Variation due to position in a species within an age group

Analysis of variance conducted showed that there is no significant difference in coefficient of flexibility due to the interactions between age and position within species. The summarized results are presented in Table 33 and Figure 34.

The values showed a decreasing trend in *Pinus caribaea* from pith (84.41) to periphery position (76.73) in 28 years old plantation (Fig. 34A). But in *Pinus patula* and *Pinus oocarpa*, coefficient of flexibility was found to increase from pith to middle position and decreases at the periphery position. In *Pinus patula*, the values were found to range from 83.80 at pith, 83.89 at middle and 75.95 at periphery position. In *Pinus oocarpa*, it ranged from 81.24 at pith, 81.77 at middle and 79.58 at periphery position.

From Figure 34B it can be seen that the coefficient of flexibility of 31 years old plantation was found to decrease from pith to periphery position in all the three pine species. In *Pinus caribaea*, it ranged from 73.25 to 82.78, in *Pinus patula* it ranged from 65.74 to 89.63 and in *Pinus oocarpa* it was found to range from 64.25 to 80.43.

In the 32 years old plantation, the coefficient of flexibility values in *Pinus oocarpa* was found to decrease from pith (83.52) to periphery (73.76) position (Fig. 34C), while the values were found to decrease from pith to middle and then increased at periphery position in *Pinus caribea* and *Pinus patula*. *Pinus caribea* had value ranging from 88.06 at pith, 80.89 at middle and 82.68 at periphery position. On the other hand, *Pinus patula* had values ranging from 86.99 at pith, 76.96 at middle and 77.44 at periphery position.

Table 33. Mean coefficient of flexibility at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Coefficient of flexibility		
28	*Pinus caribaea*	84.95 (3.05)	84.41 (5.18)	76.73 (3.26)
	Pinus patula	83.80 (3.40)	83.89 (4.60)	75.95 (4.13)
	Pinus oocarpa	81.24 (1.58)	81.77 (5.31)	79.58 (7.44)
31	*Pinus caribaea*	82.78 (3.66)	79.82 (3.29)	73.25 (11.83)
	Pinus patula	89.63 (1.36)	67.93 (12.11)	65.74 (5.30)
	Pinus oocarpa	80.43 (4.75)	77.08 (5.32)	64.25 (20.80)
32	*Pinus caribaea*	88.06 (3.46)	80.89 (3.46)	82.68 (2.09)
	Pinus patula	86.99 (3.97)	76.96 (11.05)	77.44 (2.16)
	Pinus oocarpa	83.52 (3.57)	75.63 (11.67)	73.76 (6.24)
35	*Pinus caribaea*	78.63 (2.89)	80.12 (7.01)	71.09 (16.97)
	Pinus patula	84.82 (6.24)	77.66 (12.79)	61.91 (11.70)
	Pinus oocarpa	82.59 (3.56)	80.05 (4.75)	67.27 (20.66)
F value	0.77^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

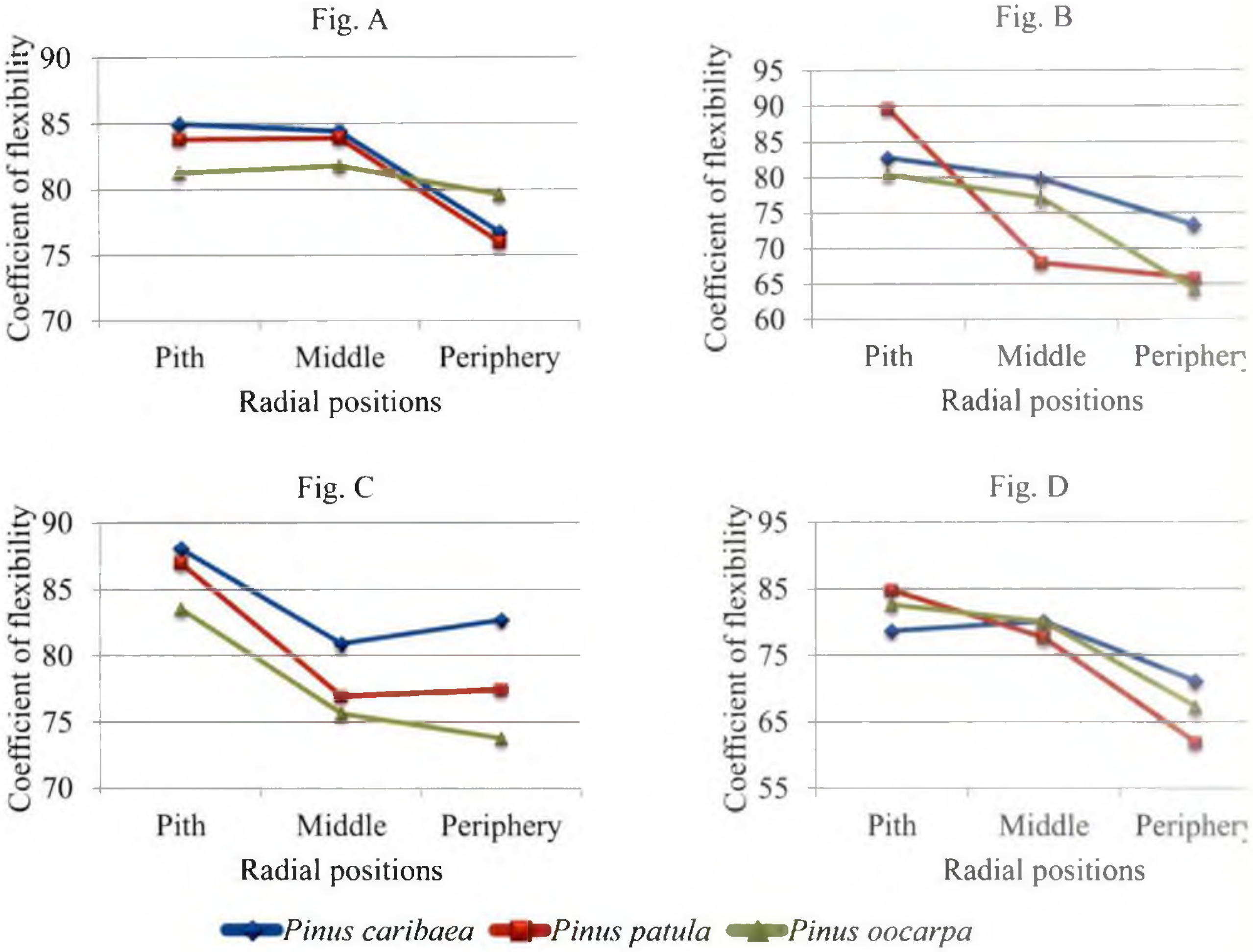

Fig. 34. Radial variation of coefficient of flexibility in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

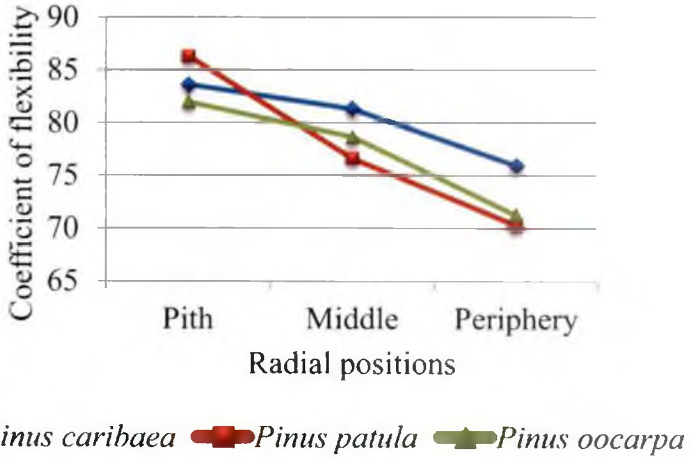

Fig. 35. Radial variation in mean coefficient of flexibility of pine species averaged over all ages

The coefficient of flexibility values was found to decrease from pith to periphery position in *Pinus patula* (84.82 to 61.91) and *Pinus oocarpa* (82.59 to 67.27) which belonged to 35 years old plantation (Fig. 34D). However, in *Pinus caribaea*, coefficient of flexibility was found to have a marginal increase from pith (78.63) to middle (80.12) and then decreased at the periphery (71.09) position.

4.2.1.8c Variation due to position within species averaged across all ages

The summarized data on variation in coefficient of flexibility in radial positions of three species across all ages are presented in Table 34 and Figure 35. Analysis of variance conducted revealed that this variation between species is highly significant at 1 per cent level and age did not have any influence on this variation (Table 34).

Table 34. Mean coefficient of flexibility of pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Coefficient of flexibility		
Pith	83.61^a (4.55)	86.31^a (4.22)	81.94^a (3.28)
Middle	81.31^a (4.65)	76.61^b (10.85)	78.63^{ab} (6.74)
Periphery	75.94^a (10.07)	70.26^b (9.02)	71.21^b (14.55)
F value	6.00** (for comparing between position within a species)		
C.D	9.41		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

From Figure 35 it can be seen that there is a decreasing trend in values from pith to periphery position in all the three species that were studied. In *Pinus caribea*, the pith (83.61), middle (81.31) and periphery (75.94) position was found to be homogenous with each other. But in *Pinus patula*, the pith (86.31) positions differed significantly from middle (76.61) and periphery (70.26). While, the latter two positions were found to be homogenous with each other. On the other hand, in *Pinus oocarpa*, the pith (81.94) differed significantly from periphery (71.21) and the middle (78.63) position was found to be homogenous with the other two radial positions.

4.2.1.9 Coefficient of rigidity

4.2.1.9a Variation due to age and species

Results of analysis of variance showed that the interactions between age and species are not significant with respect to coefficient of rigidity. Species mean across ages was also found to have no significant difference from each other. The results are presented in Table 35 and Figure 36.

The coefficient of rigidity values of each species within different ages are illustrated graphically in Figure 36A. It can be seen that in the 28 years old plantation, coefficient of rigidity was found to range from 17.97 (*Pinus caribaea*) to 19.14 (*Pinus oocarpa*), in the 31 years old plantation it ranged from 21.38 (*Pinus caribaea*) to 26.08 (*Pinus oocarpa*), in the 32 years old plantation it ranged from 16.12 (*Pinus caribaea*) to 22.37 (*Pinus oocarpa*) and in the 35 years old plantation it ranged from 23.36 (*Pinus oocarpa*) to 25.20 (*Pinus patula*).

In *Pinus caribaea*, the values of coefficient of rigidity was found to range from 16.12 (32 years old plantation) to 23.39 (35 years old plantation). On the other hand in *Pinus patula* it was found to range from 18.79 (28 years old plantation) to 25.57 (31 years old plantation). The values ranged from 19.14 (28 years old plantation) to 26.08 (31 years old plantation) in *Pinus oocarpa* (Table 35 and Fig. 36A)

Table 35. Mean coefficient of rigidity in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Coefficient of rigidity				
Pinus caribaea	17.97 (5.25)	21.38 (7.67)	16.12 (4.19)	23.39 (10.20)	19.72 (7.47)
Pinus patula	18.79 (5.29)	25.57 (13.23)	19.54 (7.73)	25.20 (13.70)	22.27 (10.63)
Pinus oocarpa	19.14 (4.74)	26.08 (13.25)	22.37 (8.19)	23.36 (12.89)	22.74 (10.24)
F value	0.36^{ns} (for comparing between age and species) 1.55^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

The species mean averaged over all ages showed no significant difference among the three pine species included in the study. The mean values are presented in Table 35 and Figure 36B. From this, it can be found out that *Pinus caribaea* had the lowest value (19.72) and *Pinus oocarpa* had the highest value (22.74) for coefficient of rigidity. However, *Pinus patula* (22.27) was found to have moderate values for coefficient of rigidity compared to the other two pine species.

4.2.1.9b Variation due to position in a species within an age group

The mean coefficient of rigidity at the different radial positions of three pine species belong to different ages are summarized in Table 36 and illustrated in Figure 37. Analysis of variance showed no significant difference between positions in the three pine species.

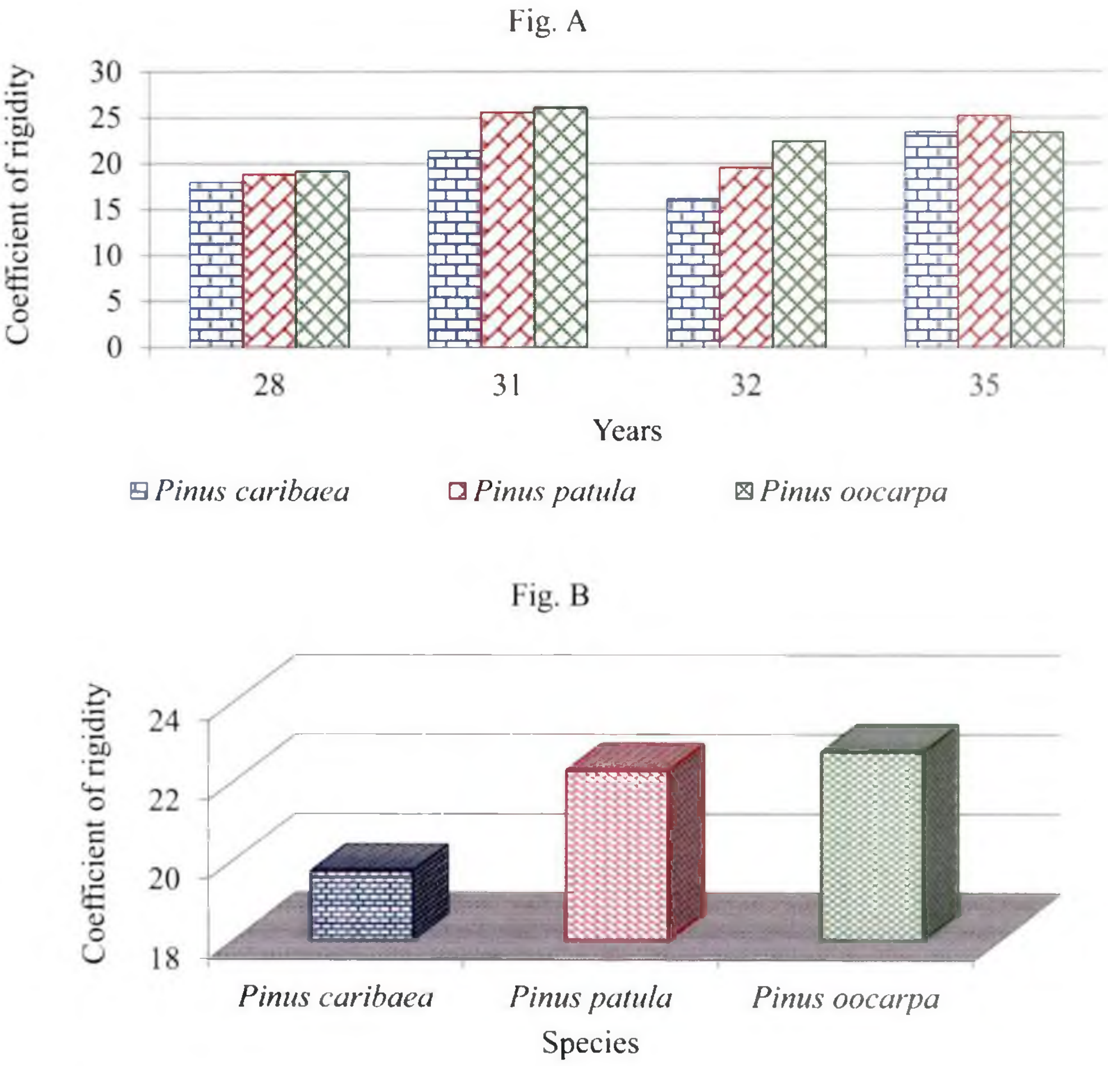

Fig.36. Variation in coefficient of rigidity between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

Table 36. Mean coefficient of rigidity at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Coefficient of rigidity		
28	*Pinus caribaea*	15.05 (3.05)	15.59 (5.18)	23.27 (3.26)
	Pinus patula	16.20 (3.40)	16.11 (4.60)	24.05 (4.13)
	Pinus oocarpa	18.76 (1.58)	18.23 (5.31)	20.42 (7.44)
31	*Pinus caribaea*	17.22 (3.66)	20.18 (3.29)	26.75 (11.83)
	Pinus patula	10.37 (1.36)	32.07 (12.11)	34.26 (5.30)
	Pinus oocarpa	19.57 (4.75)	22.92 (5.32)	35.75 (20.80)
32	*Pinus caribaea*	11.94 (3.46)	19.11 (3.46)	17.32 (2.09)
	Pinus patula	13.01 (3.97)	23.04 (11.05)	22.56 (2.16)
	Pinus oocarpa	16.48 (3.57)	24.37 (11.67)	26.24 (6.24)
35	*Pinus caribaea*	21.37 (2.89)	19.88 (7.01)	28.91 (16.97)
	Pinus patula	15.18 (6.24)	22.34 (12.79)	38.09 (11.70)
	Pinus oocarpa	17.41 (3.56)	19.95 (4.75)	32.73 (20.66)
F value	0.77^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

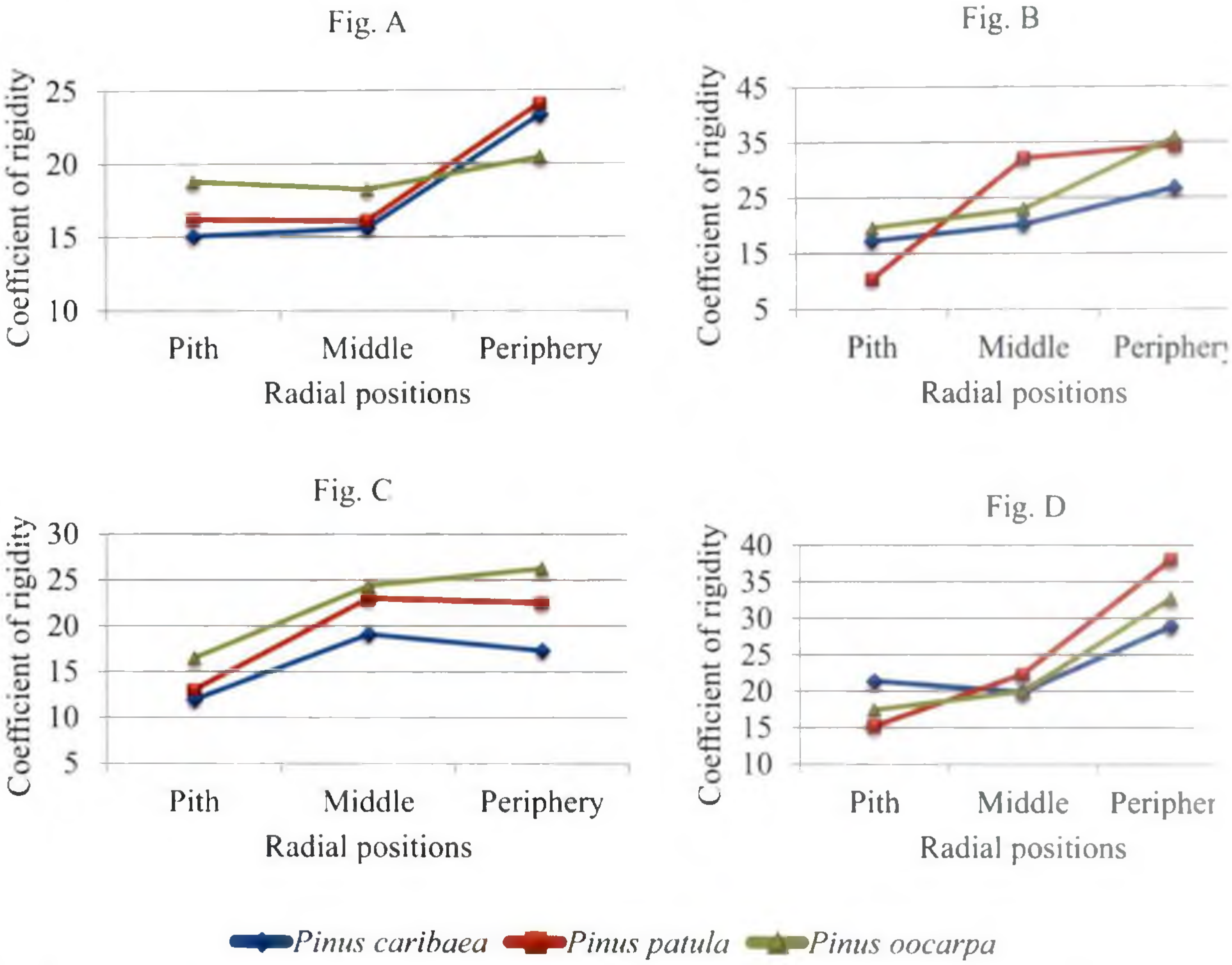

Fig. 37. Radial variation of coefficient of rigidity in pine species belonging to different age (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

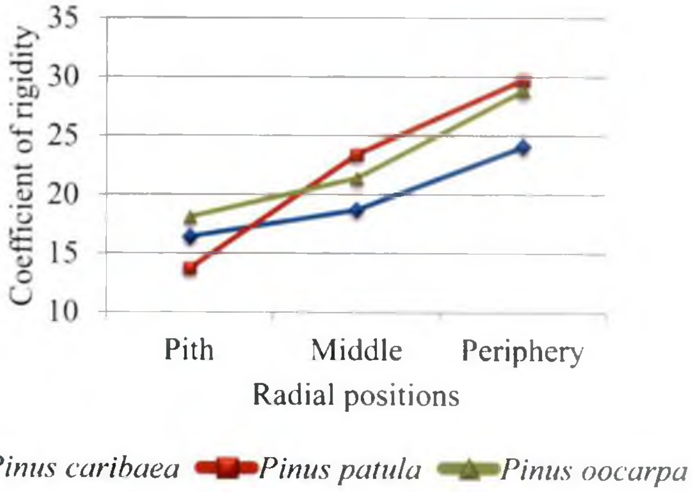

Fig. 38. Radial variation in mean coefficient of rigidity of pine species averaged over all ages

In 28 years old plantation, *Pinus caribaea* was found to have an increase in coefficient of rigidity values from pith to periphery (Fig. 37A). The values ranged from 15.05 to 23.27. In the case of *Pinus patula* and *Pinus oocarpa* the values showed a decrease from pith to middle and then increased at the periphery position. From Table 36, it can be seen that in *Pinus patula,* the coefficient of rigidity showed a range of 16.11 at middle to 24.05 at periphery. In *Pinus oocarpa*, the minimum coefficient of rigidity was 18.23 (middle) and the maximum was 20.42 (periphery).

The coefficient of rigidity values were found to have an increase from pith to periphery in the three pine species belonging to 31 years old plantation. These results are illustrated graphically in Figure 37B. *Pinus caribaea* had values ranging from 17.22 to 26.75, in *Pinus patula* it ranged from 10.37 to 34.26 and in *Pinus oocarpa* the range was found to vary from 19.57 to 35.75.

Radial values of coefficient of rigidity in 32 years old plantation is graphically illustrated in Figure 37C. From this, it can found out that both *Pinus caribaea* and *Pinus patula* had maximum value for coefficient of rigidity at middle position. However, *Pinus oocarpa* was found to have higher values for coefficient of rigidity at periphery. In *Pinus caribaea*, the values were found to range from 11.94 at pith and 19.11 at middle position. In *Pinus patula*, it ranged from 13.01 (pith) to 23.04 (middle) and in *Pinus oocarpa* it ranged from 16.48 (pith) to 26.24 (periphery).

Radial variation in 35 years old plantation showed an increase in coefficient of rigidity from pith to periphery positions in the three pine species such as *Pinus caribaea* (21.37 to 28.91), *Pinus patula* (15.18 to 38.09) and *Pinus oocarpa* (17.41 to 32.73). Figure 37D illustrates these results.

4.2.1.9c Variation due to position within species averaged across all ages

Coefficient of rigidity across all ages was found to differ significantly among the radial positions in the three pine species. The results are presented in Table 37 and Figure 38.

Table 37. Mean coefficient of rigidity in pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Coefficient of rigidity		
Pith	16.39^{a} (4.55)	13.69^{b} (4.22)	18.06^{b} (3.28)
Middle	18.69^{a} (4.65)	23.39^{a} (10.85)	21.37^{ab} (6.74)
Periphery	24.06^{a} (10.07)	29.74^{a} (9.02)	28.79^{a} (14.55)
F value	6.00** (for comparing between position within a species)		
C.D	9.41		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

From Figure 38, it can be seen that all the three species showed increase in coefficient of rigidity values from pith to periphery position and this variation is not influenced by age (Table 36). In *Pinus caribaea*, pith (16.39), middle (18.69) and periphery (24.06) were found to be homogenous, whereas in *Pinus patula*, both middle (23.39) and periphery (29.74) were found to be homogenous and these two differed significantly from the pith (13.69) position. On the other hand, the middle (21.37) position was found to be homogenous with pith (18.06) and periphery (28.79), and the latter two were significantly different with each other in *Pinus oocarpa*.

4.2.2 Ray morphology

4.2.2.1 Ray height

4.2.2.1a Variation due to age and species

Results of analysis of variance show that the interaction between age and species is significant with regard to ray height at 5 per cent level. However, species variation in ray height averaged across all ages was found to be non significant among the three pine species that were studied. Results showing the comparison between age means within species and between species averaged across all age levels are presented in Tables 38 and Figure 39.

Table 38. Mean ray height in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Ray height (µm)				
Pinus caribaea	$194.30^{a\,B}$ (17.78)	$229.95^{a\,AB}$ (24.79)	$193.52^{a\,B}$ (33)	$251.22^{a\,A}$ (34.02)	217.25 (36.67)
Pinus patula	$201.39^{a\,A}$ (33.46)	$220.78^{a\,A}$ (34.81)	$191.92^{a\,A}$ (24.6)	$218.68^{a\,A}$ (27.13)	208.19 (31.44)
Pinus oocarpa	$175.28^{a\,B}$ (19.07)	$243.36^{a\,A}$ (38.73)	$203.30^{a\,AB}$ (18.93)	$216.62^{a\,AB}$ (19.69)	209.64 (34.86)
F value	2.63* (for comparing between age and species) 1.19^{ns} (for comparing species averaged over all ages)				
C.D	45.09				

* Significant at 5 % level; ns - non significant; values within parentheses is standard deviation; means with same lower case letter as superscript in a column are homogeneous; means with same upper case letters as superscript in a row are homogeneous

From Table 38, it can be seen that there is no significant variation between species within each age level. In the case of 28 years old plantation, *Pinus patula*

Fig. A

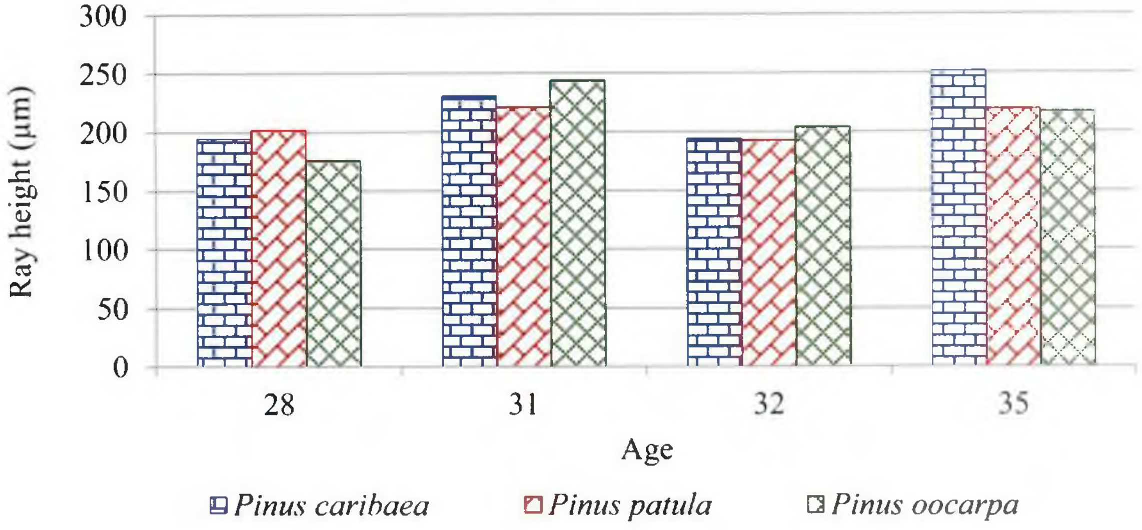

Fig. B

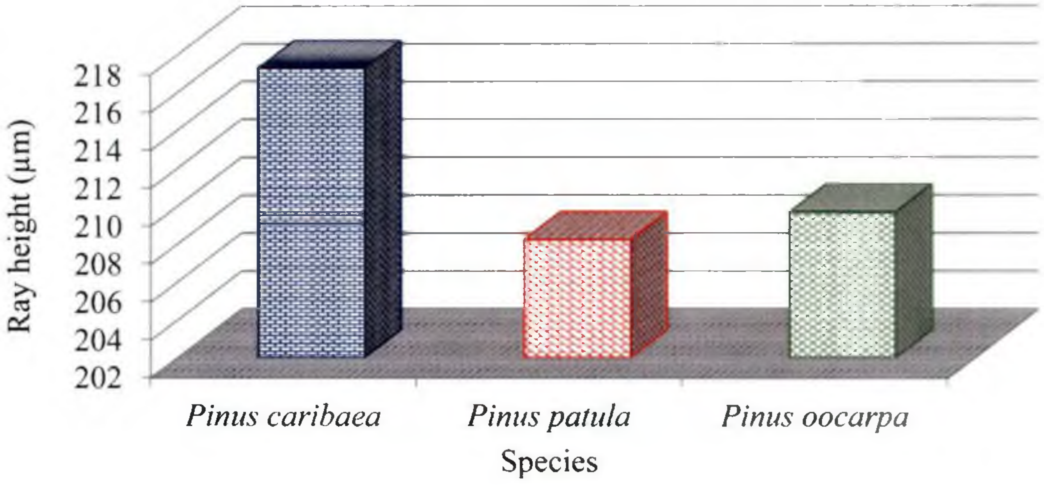

Fig. 39. Variation in ray height between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

(201.39 µm) had the maximum ray height followed by *Pinus caribaea* (194.30 µm) and *Pinus oocarpa* (175.28 µm). However, in 31 years old plantation *Pinus patula* (220.78 µm) had the lowest value for ray height followed by *Pinus caribaea* (229.95 µm) and *Pinus oocarpa* (243.36 µm). Similarly in 32 years old plantation, *Pinus patula* (191.92 µm) had the lowest value for ray height followed by *Pinus caribaea* (193.52 µm) and *Pinus oocarpa* (203.30 µm). While in 35 years old plantation, ray height values ranged from 251.22 µm in *Pinus caribaea* followed by *Pinus patula* (218.68 µm) and *Pinus oocarpa* (216.62 µm). These values are plotted graphically in Figure 39A.

The variation in ray height due to age within a species was found to differ statistically among the two pine species viz. *Pinus caribaea* and *Pinus oocarpa.* In *Pinus patula*, there was no difference among ray height values at different age levels. These results are presented in Table 38 and Figure 39A. In the case of *Pinus caribaea,* ray height values were found to be homogenous between 28, 31 and 32 years old plantations (194.30 µm, 229.95 µm and 193.52 µm respectively), while, 35 years old plantation (251.22 µm) differed significantly from 32 and 28 years old plantations in terms of ray height. Similarly, there was no significant difference between 35 and 31 year old plantation. In the case of *Pinus patula*, the ray height was maximum 31 year old plantation (220.78 µm) and lowest in the 32 year old plantation (191.92 µm), whereas in the case of *Pinus oocarpa,* the ray height values were found to differ significantly between the 28 and 31 year old plantations (175.28 µm and 243.36 µm respectively). A statistical comparison reveals that these two plantations were found to be homogenous with 32 and 35 year old plantations (203.30 µm and 216.62 µm respectively).

A comparison of ray height averaged over all ages showed no significant difference between the three pine species that were studied. These mean values were illustrated graphically in Figure 39B. From this it can be seen that, *Pinus caribaea*

(217.25 µm) had higher value and this was followed by *Pinus oocarpa* (209.64 µm). *Pinus patula* (208.19 µm) which had a moderate value.

4.2.2.1b Variation due to position in a species within an age group

The analysis of variance carried out to find out radial variation in ray height within the species at different age levels were found to be non significant. These results are presented in Table 39 and Figure 40.

From Table 39 and Figure 40A, it can be seen that in the case of 28 year old plantation the values for ray height ranges from 185.00 µm to 205.11 µm in *Pinus caribaea*, 168.96 µm to 222.09 µm in *Pinus patula* and 169.23 µm to 180.90 µm in *Pinus oocarpa*. In all the three species, pith position had the lowest value and periphery position had the highest value for ray height.

In 31 year old plantation, both *Pinus caribaea* and *Pinus patula* was found to have lowest value for ray height at pith position (208.19 µm and 184.80 µm respectively) and highest value at periphery position (249.90 µm and 243.69 µm respectively). On the other hand *Pinus oocarpa* had values ranging from 234.85 µm at periphery to 251.53 µm at pith position. These results are presented in Table 39 and Figure 40B.

The results on average values of ray height in three pine species belonging to 32 years of age is presented in Table 39 and Figure 40C. From this, it can be seen that in *Pinus caribaea* the values ranged from 174.97 µm (middle) to 222.71 µm (periphery). In *Pinus patula* it ranged from 176.27 µm (pith) to 217.85 µm (periphery) and *Pinus oocarpa* had values that ranges from 197.03 µm (middle) to 212.61 µm (periphery).

Table 39. Mean ray height at pith, middle and periphery in pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Ray height (µm)		
28	*Pinus caribaea*	185.00 (21.18)	192.79 (15.50)	205.11 (16.33)
	Pinus patula	168.96 (26.64)	213.11 (29.99)	222.09 (21.07)
	Pinus oocarpa	169.23 (14.10)	175.71 (17.02)	180.90 (29.40)
31	*Pinus caribaea*	208.19 (15.41)	231.77 (26.03)	249.90 (15.19)
	Pinus patula	184.80 (15.60)	233.86 (16.42)	243.69 (36.74)
	Pinus oocarpa	251.53 (42.68)	243.71 (62.16)	234.85 (10.34)
32	*Pinus caribaea*	182.89 (19.94)	174.97 (2.79)	222.71 (44.57)
	Pinus patula	176.27 (18.50)	181.66 (13.53)	217.85 (19.02)
	Pinus oocarpa	200.25 (12.77)	197.03 (14.01)	212.61 (29.51)
35	*Pinus caribaea*	228.43 (20.32)	265.77 (35.76)	259.45 (41.71)
	Pinus patula	191.84 (16.61)	227.85 (29.27)	236.35 (11.66)
	Pinus oocarpa	226.73 (32.59)	209.65 (14.60)	213.47 (5.86)
F value	0.55^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

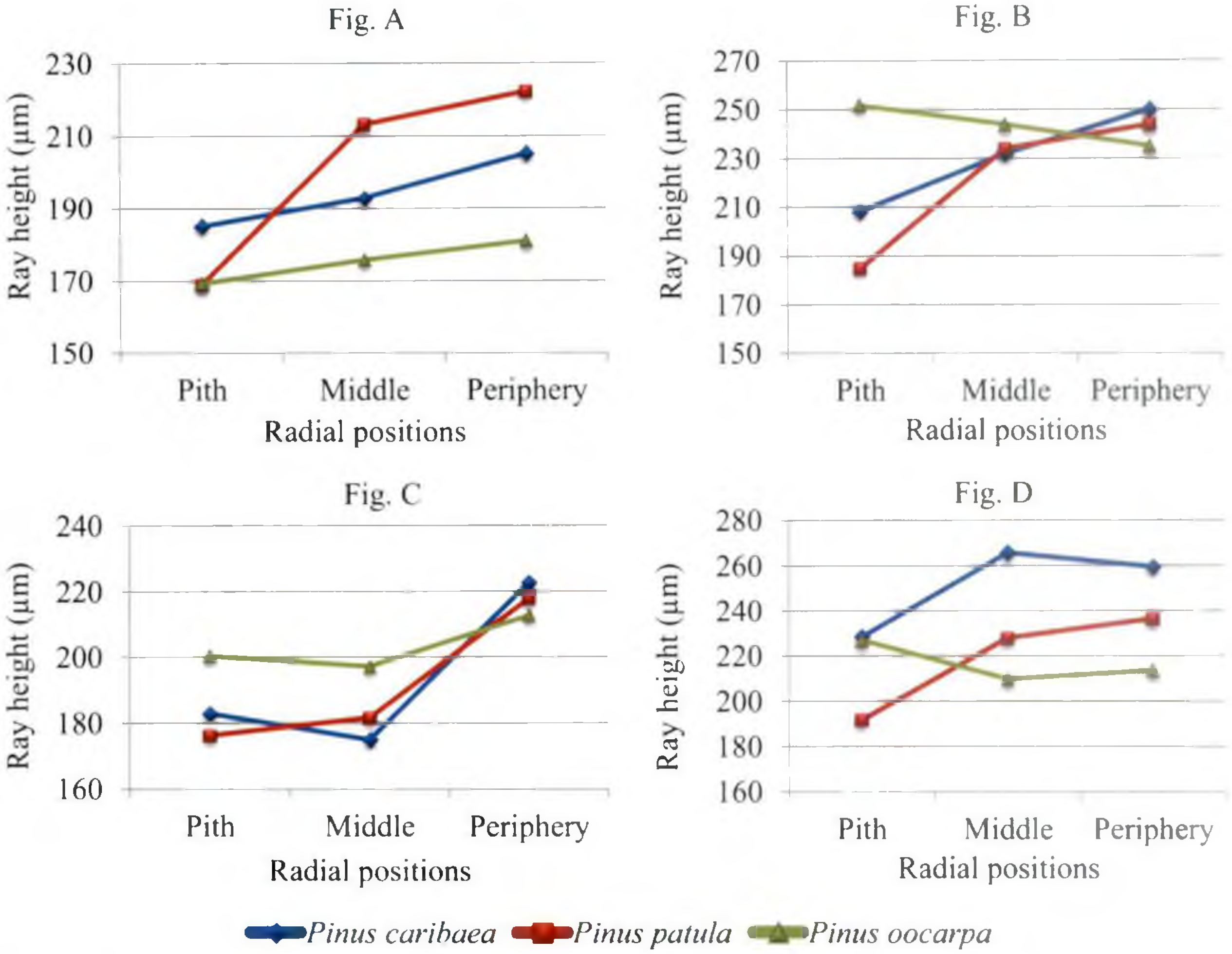

Fig. 40. Radial variation of tracheid height in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

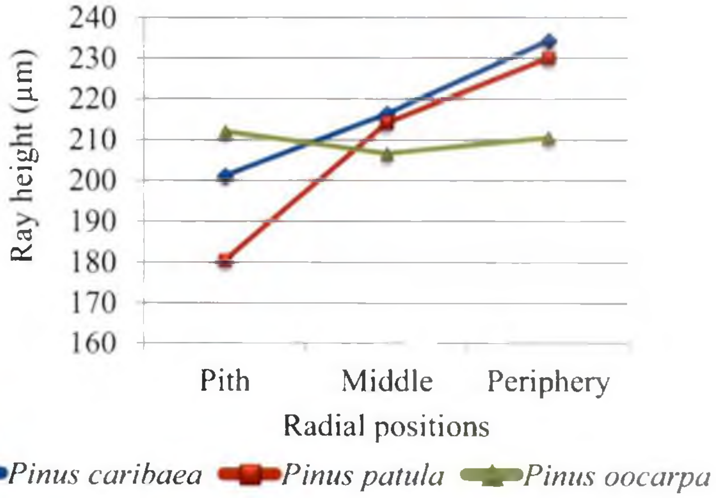

Fig. 41. Radial variation in mean ray height of pine species averaged over all ages

From Table 39 and Figure 40D, it can be seen that in *Pinus caribaea,* ray height values were found to range from 228.43 µm (pith) to 265.77 µm (middle), while *Pinus patula* had values that ranged from 191.84 µm (pith) to 236.35 µm (periphery). *Pinus oocarpa* had lowest value for ray height at middle position (209.65 µm) and highest value at pith position (226.73 µm).

4.2.2.1c Variation due to position within species averaged across all ages

Results of analysis of variance conducted showed highly significant variation in ray height with respect to position within each species (1 % level). Here, species mean averaged across all the ages in different radial positions were taken for comparison (Table 40 and Fig. 41).

Table 40. Mean ray height in pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Ray height (µm)		
Pith	201.13^{b} (25.51)	180.47^{b} (19.16)	211.94^{a} (40.15)
Middle	216.33^{ab} (41.83)	214.12^{a} (29.1)	206.52^{a} (38.64)
Periphery	234.30^{a} (35.72)	230.00^{a} (23.15)	210.46^{a} (27.30)
F value	5.89** (for comparing between position within a species)		
C.D	21.06 (for comparing between position within a species)		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

From Table 40, it can be seen that the values were found to show an increasing trend from pith to periphery position in *Pinus caribaea* and *Pinus patula*, whereas in *Pinus oocarpa*, ray height was found to decrease from pith (211.94 µm) to middle position (206.52 µm) and then it increased slightly towards periphery position (210.46 µm). In this species, there is no significant difference between the three radial positions. In *Pinus patula*, pith (180.47 µm) differed significantly from middle (214.12 µm) and periphery position (230.00 µm). *Pinus caribaea* also showed significant difference among the three radial positions studied. In this, pith (201.13 µm) differed significantly from periphery (234.30 µm). While middle position (216.33 µm) was found to be homogenous with both pith and periphery positions with regard to ray height.

4.2.2.2 Ray width

4.2.2.2a Variation due to age and species

The data on variation in ray width with respect to age and species is presented in Table 41 and Figure 42. Analysis of variance conducted revealed that age and species interaction was significant at 5 per cent level. On the other hand, species variation across all ages was found to be highly significant at 1 per cent level of variance.

From Table 41, it can be seen that there is no significant difference between the three pine species in 28, 32 and 35 years old plantations. But in 31 years old plantation, *Pinus patula* (12.64 µm) was found to differ significantly from *Pinus caribaea* (17.99 µm), while *Pinus oocarpa* (13.74 µm) had ray width values homogenous with the other two pine species. In 28 years old plantation, the ray width values ranged from 13.36 µm (*Pinus patula*) to 17.16 µm (*Pinus caribaea*), in 32 years old plantation it varied from 13.90 µm (*Pinus patula*) to 16.50 µm (*Pinus oocarpa*) and in 35 year old plantation it varied from 12.77 µm

(*Pinus oocarpa*) to 14.43 µm (*Pinus caribaea*). These results are graphically illustrated in Figure 42A.

Table 41. Mean ray width in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Ray width (µm)				
Pinus caribaea	$17.16^{a\,A}$ (2.65)	$17.99^{a\,A}$ (2.62)	$15.08^{a\,A}$ (2.15)	$14.43^{a\,A}$ (1.63)	16.16^{a} (2.65)
Pinus patula	$13.36^{a\,A}$ (2.35)	$12.64^{b\,A}$ (1.01)	$13.90^{a\,A}$ (2.19)	$14.03^{a\,A}$ (2.26)	13.48^{b} (2.02)
Pinus oocarpa	$13.98^{a\,A}$ (2.06)	$13.74^{ab\,A}$ (2.14)	$16.50^{a\,A}$ (2.2)	$12.77^{a\,A}$ (1.56)	14.25^{ab} (2.37)
F value	2.67* (for comparing between age and species) 8.79** (for comparing species averaged over all ages)				
C.D	4.697				

** Significant at 1 % level; * Significant at 5 % level; C.D - critical difference; values within parentheses is standard deviation; means with same lower case letter as superscript in a column are homogeneous; means with same upper case letters as superscript in a row are homogeneous

There is no significant difference in ray width values between different age levels within each species (Table 41). In the case of *Pinus caribaea*, the values ranged from 14.43 µm (35 years old plantation) to 17.99 µm (31 years old plantation), in *Pinus patula* it ranged from 12.64 µm (31 years old plantation) to 13.90 µm (32 years old plantation) and in *Pinus oocarpa* it ranged from 12.77 µm (35 years old plantation) to 16.50 µm (32 year old plantation) (Fig. 42A).

Species mean averaged over all ages showed significant difference between the three species. *Pinus caribaea* (16.16) differed significantly from *Pinus patula*

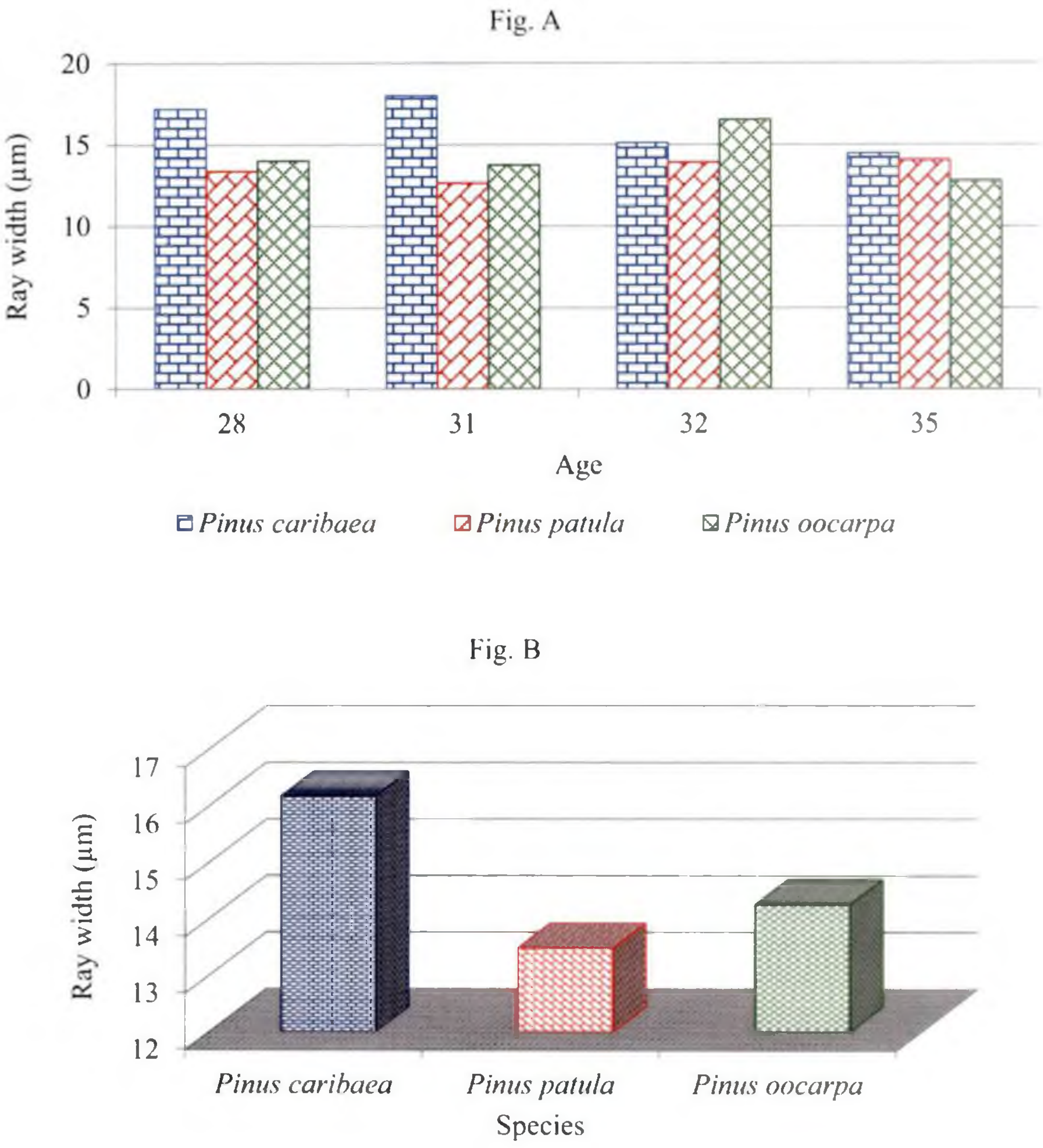

Fig. 42. Variation in ray width between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

(13.48), whereas *Pinus oocarpa* (14.25) was found to be homogenous with other two species (Fig. 42B)

4.2.2.2b Variation due to position in a species within an age group

Analysis of variance conducted showed that there is no significant difference in the interaction between age and position within species. The summarized results are presented in Table 42 and Figure 43.

From Table 42 and Figure 43A, it can be seen that in 28 year old plantation both *Pinus caribaea* and *Pinus oocarpa* had higher values for ray width at pith position (18.26 µm and 16.06 µm respectively) and lower values at middle position (15.40 µm and 12.91 µm respectively). On the other hand in *Pinus patula,* the values showed a decreasing trend from pith (14.59 µm) to periphery (12.01 µm).

In 31 year old plantation, *Pinus caribaea* showed a decreasing trend in ray width from pith (20.09 µm) to periphery (16.28 µm) position (Fig. 43B), whereas *Pinus patula* had higher value for ray width at middle position (13.27 µm) and lower value (12.32 µm) at both periphery and pith position. In the case of *Pinus oocarpa*, the higher value for ray width was found to be at pith (14.15 µm) and lower value at the middle position (13.37 µm).

From Table 42 and Figure 43C, it can be seen that in 32 years old plantation, both *Pinus caribaea* and *Pinus oocarpa* had higher value for ray width at pith position (16.63 µm and 17.97 µm respectively). Compared to this *Pinus caribaea* had lower value at periphery position (14.15 µm), whereas *Pinus oocarpa* had lower value at middle position (15.62 µm). On the other hand *Pinus patula* had values ranges from 14.96 µm (middle) to 12.60 µm (pith).

In 35 year old plantation the ray width was found to have higher values at pith position for *Pinus caribaea* (14.81 µm) and *Pinus patula* (15.99 µm), while both

Table 42. Mean ray width at pith, middle and periphery in pine species belonging to different ages

Age	Species	Radial positions		
		Pith	**Middle**	**Periphery**
		Ray width (µm)		
28	*Pinus caribaea*	18.26 (0.22)	15.40 (4.20)	17.82 (1.80)
	Pinus patula	14.59 (2.00)	13.49 (3.18)	12.01 (1.69)
	Pinus oocarpa	16.06 (1.34)	12.91 (2.33)	12.98 (0.22)
31	*Pinus caribaea*	20.09 (1.11)	17.60 (3.43)	16.28 (1.80)
	Pinus patula	12.32 (1.32)	13.27 (0.34)	12.32 (1.14)
	Pinus oocarpa	14.15 (3.42)	13.37 (2.00)	13.71 (1.46)
32	*Pinus caribaea*	16.63 (3.27)	14.45 (1.41)	14.15 (0.64)
	Pinus patula	12.60 (2.85)	14.96 (2.02)	14.15 (1.65)
	Pinus oocarpa	17.97 (1.79)	15.62 (3.12)	15.91 (1.25)
35	*Pinus caribaea*	14.81 (0.51)	14.18 (1.36)	14.30 (2.86)
	Pinus patula	15.99 (2.62)	12.47 (1.90)	13.64 (0.58)
	Pinus oocarpa	12.06 (1.95)	13.35 (1.77)	12.91 (1.21)
F value	1.64^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

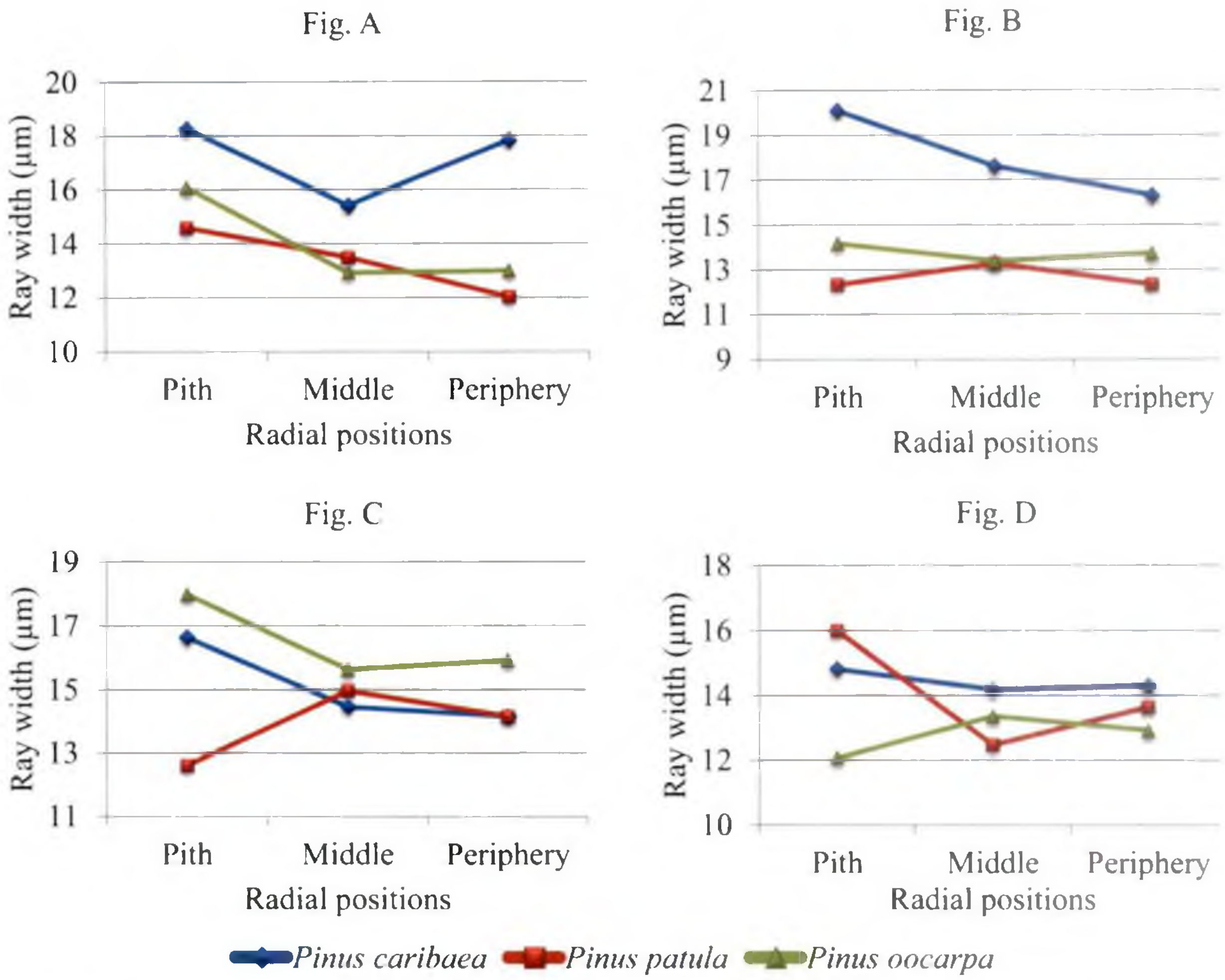

Fig. 43. Radial variation of ray width in pine species belonging to different ages: (A) 28 year (B) 31 years; (C) 32 years; (D) 35 years

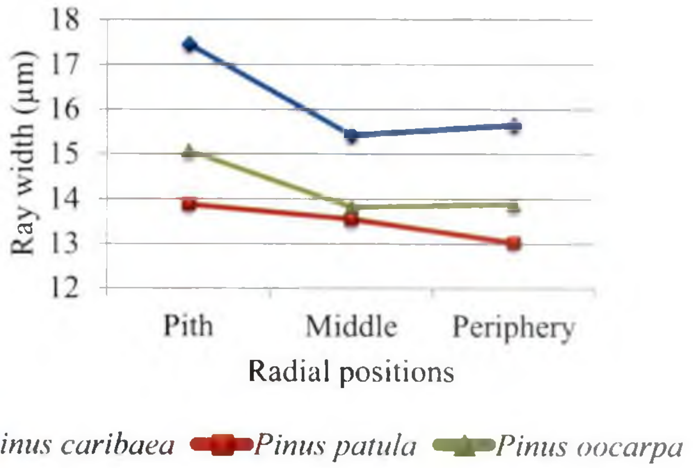

Fig. 44. Radial variation in mean ray width of pine species averaged over all ages

species had lower values for ray width at middle position i.e. 14.18 µm for *Pinus caribaea* and 12.47 µm for *Pinus patula*. Compared to this *Pinus oocarpa* had higher values at middle position (13.35 µm) and lower values at pith position (12.06 µm). These results are presented in Table 42 and Figure 43D.

4.2.2.2c Variation due to position within species averaged across all ages

The summarized data on variation of ray width in radial positions of three species across all ages are presented in Table 43 and Figure 44. Analysis of variance conducted revealed that this variation between species is significant at 5 per cent level and age did not have any influence on this variation (Table 43).

Table 43. Mean ray width in species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Ray width (µm)		
Pith	17.45^a (2.53)	13.88^a (2.50)	15.06^a (3.00)
Middle	15.41^b (2.83)	13.55^a (2.03)	13.81^a (2.30)
Periphery	15.64^b (2.29)	13.03^a (1.48)	13.88^a (1.60)
F value	3.04** (for comparing between position within a species)		
C.D	1.74 (for comparing between position within a species)		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

From Table 43, it can be seen that there is no difference with respect to ray width between the radial positions in *Pinus patula* and *Pinus oocarpa*. There was a decrease in ray width values from pith (13.88 μm) to periphery (13.03 μm) in the case of *Pinus patula*. The values ranged from 13.81 μm at middle position to 15.06 μm at pith position in *Pinus oocarpa*. Compared to these two species, *Pinus caribaea* had significant difference between radial positions. In this species, both middle (15.41 μm) and periphery (15.64 μm) positions were found to be homogenous, while pith position (17.45 μm) was found to differ significantly from the other two radial positions.

4.2.3 Tissue frequency

4.2.3.1 Tracheid frequency in earlywood

4.2.3.1a Variation due to age and species

Analysis of variance revealed that variation in earlywood tracheid frequency due to age and species was found to be significant at 5 per cent level. Species mean across all ages was also found to have highly significant difference from one another (1 per cent level). These variations in earlywood tracheid frequency have been presented in Table 44 and graphically represented in Figure 45.

Figure 45A gives a graphical representation of the comparison of earlywood tracheid frequency between pine species within different age levels. In 28 years old plantation, *Pinus caribaea* (371/mm^2) was found to differ significantly from *Pinus patula* (588/mm^2), whereas *Pinus oocarpa* (447/mm^2) was found to be homogenous with other two species. On the other hand, 31 years old plantation had no variation in earlywood tracheid frequency between the species. In this, values were found to range from 472/mm^2 (*Pinus oocarpa*) to 501/mm^2 (*Pinus patula*). Earlywood tracheid frequency in 32 years old plantation was found to have similar species variation pattern as that of 28 years old plantation. *Pinus caribaea* (414/mm^2) differed significantly from *Pinus patula* (613/mm^2), whereas *Pinus oocarpa* (453/mm^2) was found to be homogenous with other two species. In 35 years old

Table 44. Mean earlywood tracheid frequency in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Earlywood tracheid frequency (no. per mm^2)				
Pinus caribaea	$371^{b\,A}$ (52.87)	$499^{a\,A}$ (75.63)	$414^{b\,A}$ (125.17)	$414^{b\,A}$ (92.18)	424^{b} (98.43)
Pinus patula	$588^{a\,A}$ (154.04)	$501^{a\,A}$ (159.52)	$613^{a\,A}$ (129.83)	$620^{a\,A}$ (160.5)	581^{a} (152.57)
Pinus oocarpa	$447^{ab\,A}$ (102.46)	$472^{a\,A}$ (111.21)	$453^{ab\,A}$ (125.21)	$373^{b\,A}$ (27.13)	436^{b} (102.13)
F value	2.84* (for comparing between age and species) 23.82** (for comparing species averaged over all ages)				
C.D	180				

** Significant at 1 % level; * Significant at 5 % level; values within parentheses is standard deviation; means with same lower case letter as superscript in a column are homogeneous; means with same upper case letters as superscript in a row are homogeneous

plantation, *Pinus caribaea* (414/mm^2) and *Pinus oocarpa* (373/mm^2) were found to be homogenous with respect to earlywood tracheid frequency, while these two species differed significantly from *Pinus patula* (620/mm^2).

There is no significant variation in earlywood tracheid frequency within the species at different age levels (Table 44). In the case of *Pinus caribaea*, earlywood tracheid frequency was found to range from 371/mm^2 (28 years old plantation) to 499/mm^2 (31 years old plantation), while in *Pinus patula*, it was found to range from 501/mm^2 (31 years old plantation) to 620/mm^2 (35 years old plantation). On the other hand, in *Pinus oocarpa,* values were found to range from 373/mm^2 (35 years old plantation) to 472/mm^2 (31 years old plantation) (Fig. 45A).

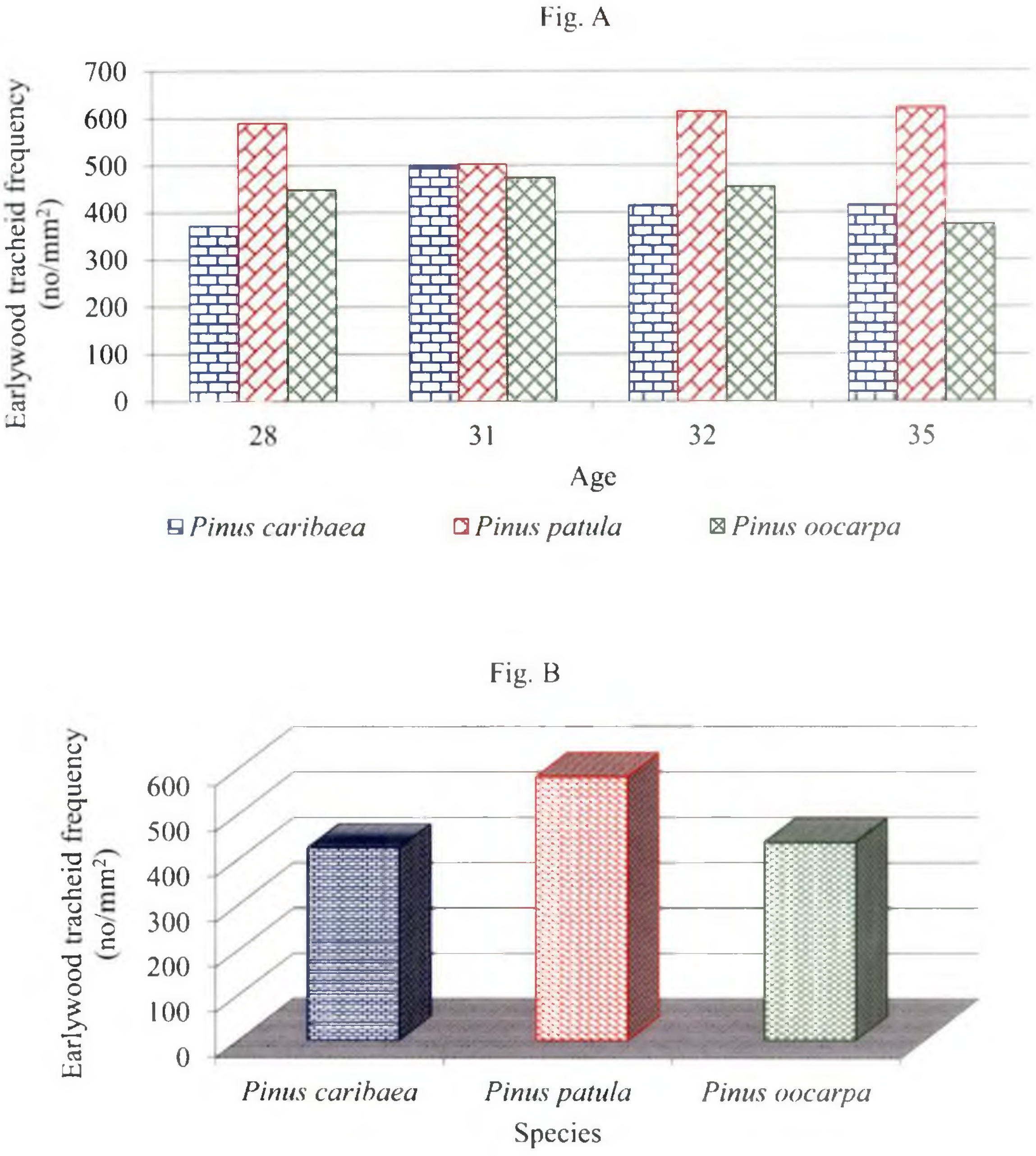

Fig. 45. Variation in earlywood tracheid frequency between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

From Table 44 and Figure 45B, it can be seen that *Pinus patula* (581/mm^2) differed significantly from *Pinus caribaea* (424/mm^2) and *Pinus oocarpa* (436/mm^2), while the latter two were found to be homogenous with each other.

4.2.3.1b Variation due to position in a species within an age group

The summarized results of mean earlywood tracheid frequency at each radial position among the three pine species belonging to different age levels are presented in Table 45 and Figure 46. Analysis of variance revealed that there is no significant variation due to position in a species within an age group.

Figure 46A gives a graphical representation of mean earlywood tracheid frequency in the pine species belonging to 28 years old plantation. In all the three species, the values were found to decrease radially i.e. from pith to periphery. *Pinus caribaea* had values ranging from 418/mm^2 to 330/mm^2. In *Pinus patula*, it ranged from 709/mm^2 to 505/mm^{2}and in *Pinus oocarpa*, it ranged from 538/mm^2 to 380/mm^2.

Similarly, in 31 years old plantation, both *Pinus patula* (672/mm^2 and 369/mm^2) and *Pinus oocarpa* (587/mm^2 and 390/mm^2) showed a decreasing trend in the earlywood tracheid frequency from pith to periphery, while *Pinus caribaea* showed a slight increase in value from pith (517/mm^2) to middle (530/mm^2) position and then it decreased at the periphery (449/mm^2). These results are illustrated in Figure 46B.

All the three species in 32 years old plantation were also found to have a decreasing trend in earlywood tracheid frequency from pith to periphery (Fig. 46C). Radially, the values ranged from 533/mm^2 to 326/mm^2 in *Pinus caribaea*. In *Pinus patula*, it ranged from 724/mm^2 to 510/mm^2 and in *Pinus oocarpa*, it ranged from 580/mm^2 to 353/mm^2.

Table 45. Mean earlywood tracheid frequency at pith, middle and periphery in pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Earlywood tracheid frequency (no. per mm^2)		
28	*Pinus caribaea*	418 (51.11)	365 (49.15)	330 (17.38)
	Pinus patula	709 (224.8)	551 (72.48)	505 (67.71)
	Pinus oocarpa	538 (49.55)	423 (128.73)	380 (56.19)
31	*Pinus caribaea*	517 (29.16)	530 (115.34)	449 (55.68)
	Pinus patula	672 (147.80)	463 (75.90)	369 (44.47)
	Pinus oocarpa	587 (109.33)	439 (24.97)	390 (72.92)
32	*Pinus caribaea*	533 (153.68)	382 (62.36)	326 (26.42)
	Pinus patula	724 (140.31)	605 (89.34)	510 (72.70)
	Pinus oocarpa	580 (137.08)	427 (43.90)	353 (42.80)
35	*Pinus caribaea*	415 (57.62)	459 (152.92)	368 (31.53)
	Pinus patula	748 (144.71)	594 (62.04)	517 (191.15)
	Pinus oocarpa	382 (33.27)	372 (1.68)	366 (40.53)
F value	0.65^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

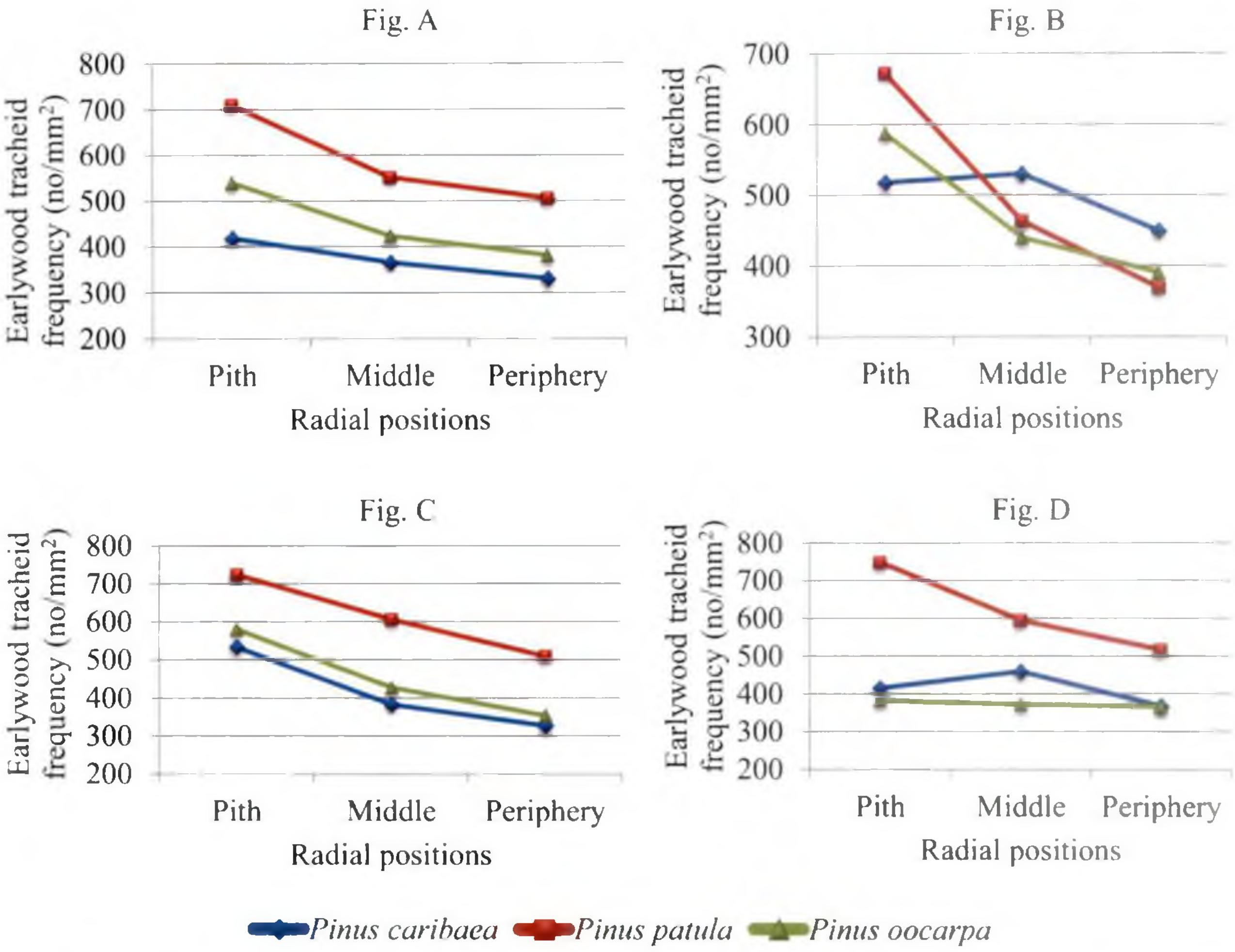

Fig. 46. Radial variation of earlywood tracheid frequency in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

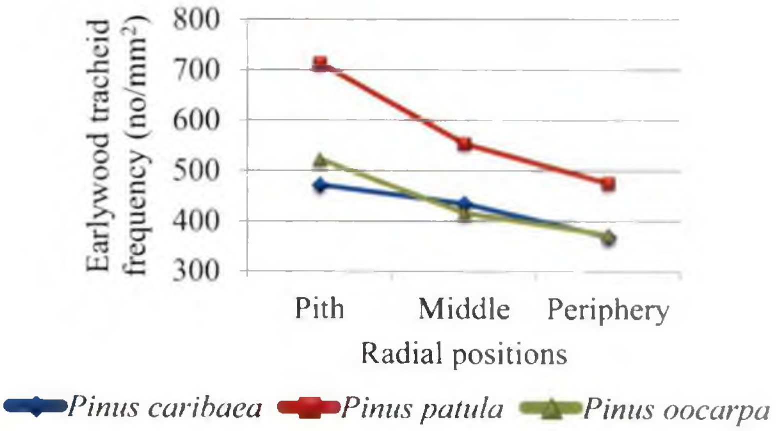

Fig. 47. Radial variation in mean earlywood tracheid frequency of pine species averaged over all ages

From Figure 46D, it can be seen that both *Pinus patula* and *Pinus oocarpa* had a decreasing trend in earlywood tracheid frequency across the radial positions (pith to periphery). In these species, the values ranged from 748/mm^{2}to 517/mm^2 (*Pinus patula*) and 382/mm^2 to 366/mm^2 (*Pinus oocarpa*). However, in *Pinus caribaea*, radially there was a slight increase in values from pith (415/mm^2) to middle (459/mm^2), while at the periphery (368/mm^2) the value decreased.

4.2.3.1c Variation due to position within species averaged across all ages

The mean earlywood tracheid frequency across all the ages within the three pine species was found to vary significantly between the three radial positions (1 % level). These results are given in Table 46 and Figure 47.

Table 46. Mean earlywood tracheid frequency in pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Earlywood tracheid frequency (no. per mm^2)		
Pith	471^a (93.81)	713^a (146.23)	522^a (117.09)
Middle	434^{ab} (111.89)	553^b (87.04)	415^b (64.87)
Periphery	368^b (60.04)	475^b (113.64)	372^b (48.86)
F value	11.74** (for comparing between position within a species)		
C.D	75 (for comparing between position within a species)		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

All the three species were found to have a decreasing pattern in the values from pith to periphery. Pith (471/mm^2) position was found to vary significantly from periphery (368/mm^2) in *Pinus caribaea*, while these two radial positions were found to be homogenous with the middle (434/mm^2) position. In *Pinus patula*, both middle (553/mm^2) and periphery (475/mm^2) position were found to be homogenous with each other, while these two differed significantly from the pith (713/mm^2) position. Similarly, in *Pinus oocarpa*, both middle (415/mm^2) and periphery (372/mm^2) position were found to be homogenous with each other, while these two differed significantly from the pith (522/mm^2) position.

4.2.3.2 Tracheid frequency in latewood

4.2.3.2a Variation due to age and species

Analysis of variance showed highly significant variation in latewood tracheid frequency due to age and species at 1 per cent variance level. It was also found that, significant variation exist among the species with respect to latewood tracheid frequency which is averaged across all ages (1 % level). But it should be noted that this species variation includes influence due to age. The results are presented in Table 47 and Figure 48.

From Table 47, it can be seen that except 32 years old plantation all other three plantations showed no significant difference among species within the respective age levels. In 28 years old plantation, *Pinus patula* (824/mm^2) had the highest value for latewood tracheid frequency, while *Pinus caribaea* (604/mm^2) had the lowest value. On the other hand, in 31 years old plantation *Pinus caribaea* (859/mm^2) had the highest value for latewood tracheid frequency, while *Pinus patula* (702/mm^2) had the lowest value. Similar to 28 years old plantation, *Pinus patula* (763/mm^2) had the highest value, while *Pinus caribaea* (639/mm^2) had the lowest value for latewood tracheid frequency in 35 years old plantation. However, in 32 years old plantation, *Pinus caribaea* (575/mm^2) was found to differ significantly from *Pinus patula* (886/mm^2), while these two had values homogenous with

Table 47. Mean latewood tracheid frequency in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Latewood tracheid frequency (no. per mm^2)				
Pinus caribaea	604$^{a\ AB}$ (118.43)	859$^{a\ A}$ (152.78)	575$^{b\ B}$ (48.58)	639$^{a\ AB}$ (111.39)	669^{b} (157.24)
Pinus patula	824$^{a\ A}$ (161.45)	702$^{a\ A}$ (63.4)	886$^{a\ A}$ (234.87)	763$^{a\ A}$ (168.78)	794^{a} (175.55)
Pinus oocarpa	747$^{a\ A}$ (68.21)	745$^{a\ A}$ (136.03)	743$^{ab\ A}$ (89.82)	649$^{a\ A}$ (85.73)	721^{ab} (102.96)
F value	4.10** (for comparing between age and species) 5.96** (for comparing species averaged over all ages)				
C.D	259				

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same lower case letter as superscript in a column are homogeneous; means with same upper case letters as superscript in a row are homogeneous

Pinus oocarpa (743/mm^2). These results are graphically illustrated in Figure 48A.

Within species variation at different age levels were found to be significant only in the case of *Pinus caribaea* (Table 47). In this, both 31 (859/mm^2) and 32 (575/mm^2) years old plantations were found to have significant difference, while these two were homogenous with 28 (604/mm^2) and 35 (639/mm^2) years old plantations. In *Pinus patula*, values ranged from 702/mm^2 (31 years old plantation) to 886/mm^2 (32 years old plantation) and in *Pinus oocarpa*, it ranged from 649/mm^2 (35 years old plantation) to 747/mm^2 (28 years old plantation). Figure 48A graphically represents these results.

Species mean in latewood tracheid frequency, averaged over all ages, was found to be significant at 1 per cent significance level. *Pinus patula* (794) differed

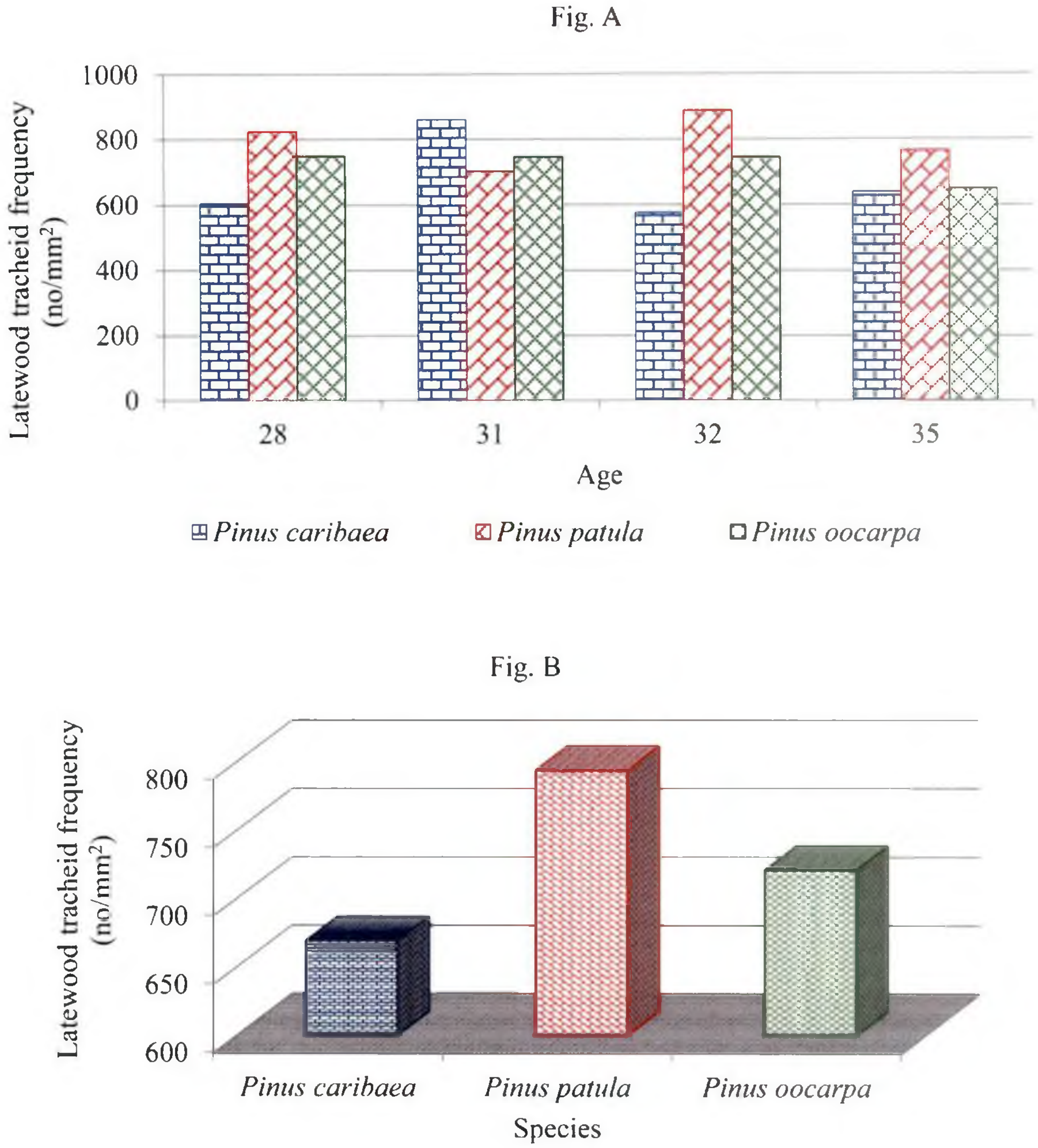

Fig. 48. Variation in latewood tracheid frequency between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

significantly from *Pinus caribaea* (669) and *Pinus oocarpa* (721), whereas later two were found to be homogenous with each other (Fig. 48B)

4.2.3.2b Variation due to position in a species within an age group

The summarized results of mean latewood tracheid frequency at radial positions of three pine species belonging to different age levels are presented in Table 48 and Figure 49. Analysis of variance revealed that this radial variation is highly significant at 1 per cent variance level.

Figure 49A graphically represents the latewood tracheid frequency at radial positions in the three pine species belonging to 28 years old plantation. Radial positions were found have homogenous values in *Pinus caribaea* and *Pinus oocarpa.* In them, values were found to range from 560/mm^2 to 682/mm^2 (*Pinus caribaea*) and 695/mm^2 to 829/mm^2 in (*Pinus oocarpa*). Among these two species, only *Pinus caribaea* had a decreasing trend in latewood tracheid frequency values along the radial positions i.e. from pith to periphery. In *Pinus patula*, pith (976/mm^2) position differed significantly from the periphery (686/mm^2), while middle (809/mm^2) position was found to be homogenous with the other two radial positions. It can also be seen that there is a decrease in values from pith to periphery position in *Pinus patula.*

In 31 years old plantation, radial variation in the latewood tracheid frequency was found to be significant only in *Pinus oocarpa* (Table 48). In this species, middle (639/mm^2) position and the pith (842/mm^2) were found to differ significantly from each other, while periphery (753/mm^2) was found to be homogenous with the other two radial positions. In the case of *Pinus caribaea*, values were found to range from 817/mm^2 (periphery) to 889/mm^2 (middle) and in *Pinus patula*, it ranged from 645/mm^2 (periphery) to 731/mm^2 (middle). These results are illustrated graphically in Figure 49B.

Table 48. Mean latewood tracheid frequency at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Latewood tracheid frequency (no. per mm^2)		
28	*Pinus caribaea*	560^{a} (134.29)	570^{a} (138.69)	682^{a} (71.41)
	Pinus patula	976^{a} (181.37)	809^{ab} (76.11)	686^{b} (47.35)
	Pinus oocarpa	829^{a} (51.07)	716^{a} (12.65)	695^{a} (14.86)
31	*Pinus caribaea*	870^{a} (107.53)	889^{a} (122.41)	817^{a} (250.43)
	Pinus patula	729^{a} (63.03)	731^{a} (65.34)	645^{a} (24.04)
	Pinus oocarpa	842^{a} (115.18)	639^{b} (40.15)	753^{ab} (166.97)
32	*Pinus caribaea*	566^{a} (53.19)	585^{a} (57.09)	575^{a} (55.46)
	Pinus patula	1196^{a} (13.44)	736^{b} (11.22)	726^{b} (60.89)
	Pinus oocarpa	811^{a} (37.60)	769^{ab} (29.25)	650^{b} (94.46)
35	*Pinus caribaea*	552^{a} (108.53)	652^{a} (126.90)	712^{a} (47.64)
	Pinus patula	769^{a} (191.48)	801^{a} (237.14)	720^{a} (127.01)
	Pinus oocarpa	703^{a} (96.65)	598^{a} (103.27)	645^{a} (34.4)
F value	3.92** (for comparing between age and position within species)			
C.D	160 (for comparing between age and position within species)			

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

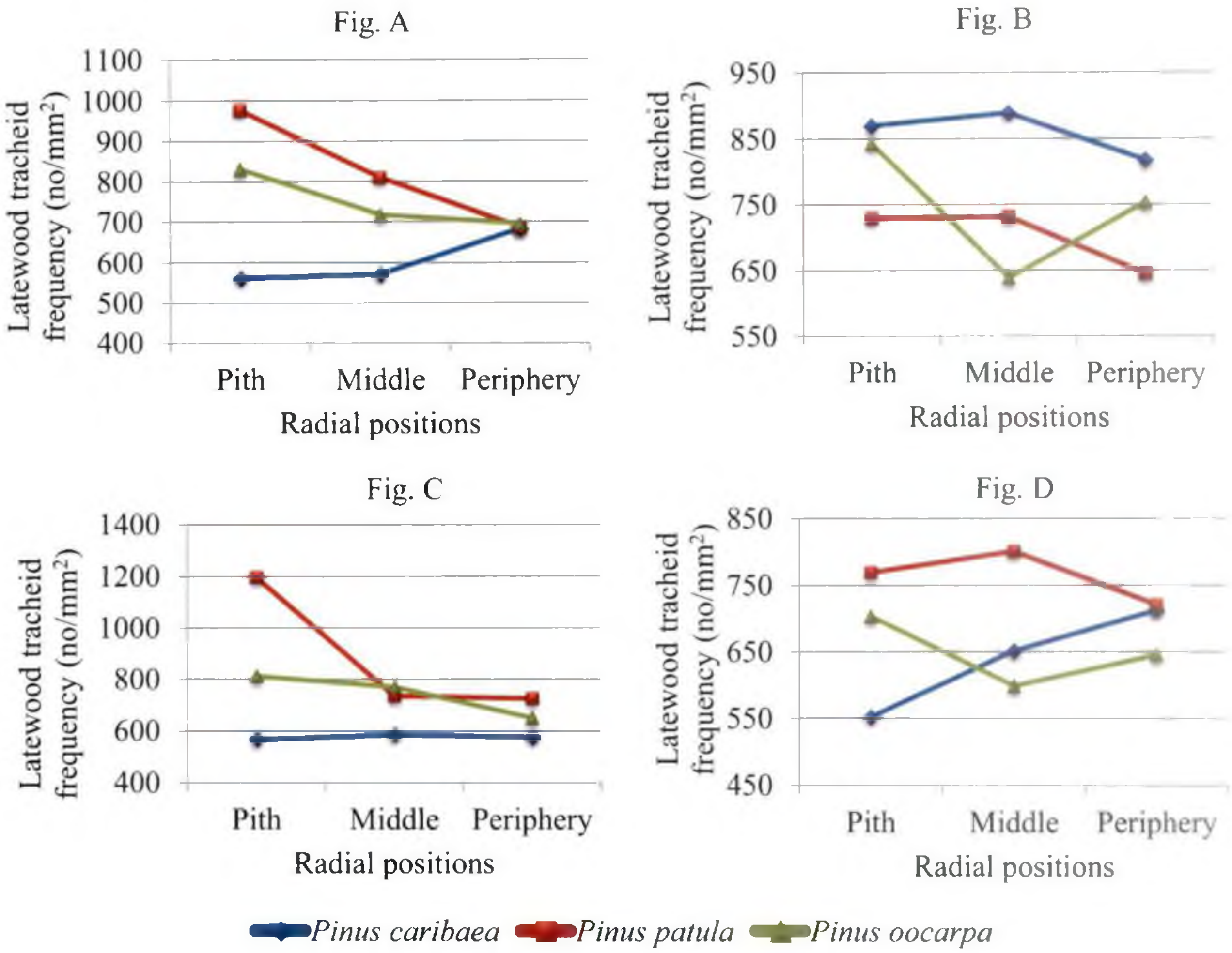

Fig. 49. Radial variation of latewood tracheid in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

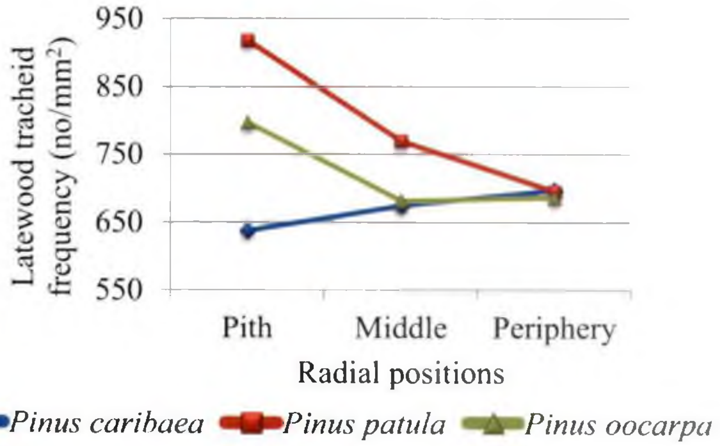

Fig. 50. Radial variation in mean latewood tracheid frequency of pine species averaged over all ages

From Figure 49C, it can be seen that in 32 years old plantation both *Pinus patula* and *Pinus oocarpa* were found to have a decreasing trend in latewood tracheid frequency across the radial positions (pith to periphery). Except *Pinus caribaea*, other two species shows radial variation in latewood tracheid frequency. In *Pinus caribaea*, values were found to range from 566/mm^2 (pith) to 585/mm^2 (middle). On the other hand, in *Pinus patula*, pith (1196/mm^2) differed significantly from middle (736/mm^2) and periphery (726/mm^2) positions, while the latter two radial positions were found to be homogenous with each other. In the case of *Pinus oocarpa*, pith (811/mm^2) differed significantly from the periphery (650/mm^2), while the middle (769/mm^2) position was found to be homogenous with the other two radial positions.

In 35 years old plantation, latewood tracheid frequency was found to have no difference radially in all the three pine species (Table 48). Figure 49D represent these results graphically. In *Pinus caribaea*, latewood tracheid frequency values were found to range from 552/mm^2 (pith) to 712/mm^2 (periphery); in *Pinus patula*, it ranged from 720/mm^2 (periphery) to 801/ mm^2 (middle) and in *Pinus oocarpa*, it ranged from 598/mm^2 (middle) to 703/mm^2 (pith).

4.2.3.2c Variation due to position within species averaged across all ages

Analysis of variance conducted suggests that radial variation in latewood tracheid frequency across all ages within the species was found to be highly significant at 1 per cent variance level. But it should be noted that this variation also includes the influence due to age (Table 48). These results are given in Table 49 and Figure 50.

From Figure 50 no specific pattern of variation was noticed radially in the three pine species. Radial variation was not significant in the case of *Pinus caribaea*.

Table 50. Mean earlywood tracheid percentage in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Earlywood tracheid percentage (%)				
Pinus caribaea	85.92 (2.15)	84.49 (2.34)	84.94 (1.93)	86.45 (1.24)	85.45 (2.03)
Pinus patula	83.76 (5.53)	84.33 (1.32)	85.97 (3.55)	85.43 (1.64)	84.87 (3.41)
Pinus oocarpa	84.41 (1.63)	86.92 (1.85)	85.94 (2.47)	83.94 (2.71)	85.30 (2.43)
F value	1.98^{ns} (for comparing between age and species) 0.43^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

From Table 50 it can be seen that, in the 28 years old plantation, the earlywood tracheid percentage was found to range from 83.76 per cent (*Pinus patula*) to 85.92 per cent (*Pinus caribaea*). In 31 years old plantation, it ranged from 84.33 per cent (*Pinus patula*) to 86.92 per cent (*Pinus oocarpa*) and in the 32 years old plantation it ranged from 84.94 per cent (*Pinus caribaea*) to 85.97 per cent (*Pinus patula*). In the 35 years old plantation, earlywood tracheid percentage ranged from 83.94 per cent (*Pinus oocarpa*) to 86.45 per cent (*Pinus caribaea*). The results are illustrated graphically in Figure 51A.

In *Pinus caribaea,* earlywood tracheid percentage was found to range from 84.49 per cent (31years old plantation) to 86.45 per cent (35 years old plantation) and in *Pinus patula* it ranged from 83.76 per cent (28 years old plantation) to 85.97 per cent (32 years old plantation). On the other hand, in *Pinus oocarpa,* earlywood tracheid percentage was found to range from 83.94 per cent (35 years old plantation) to 86.92 per cent (31 years old plantation) (Fig. 51A).

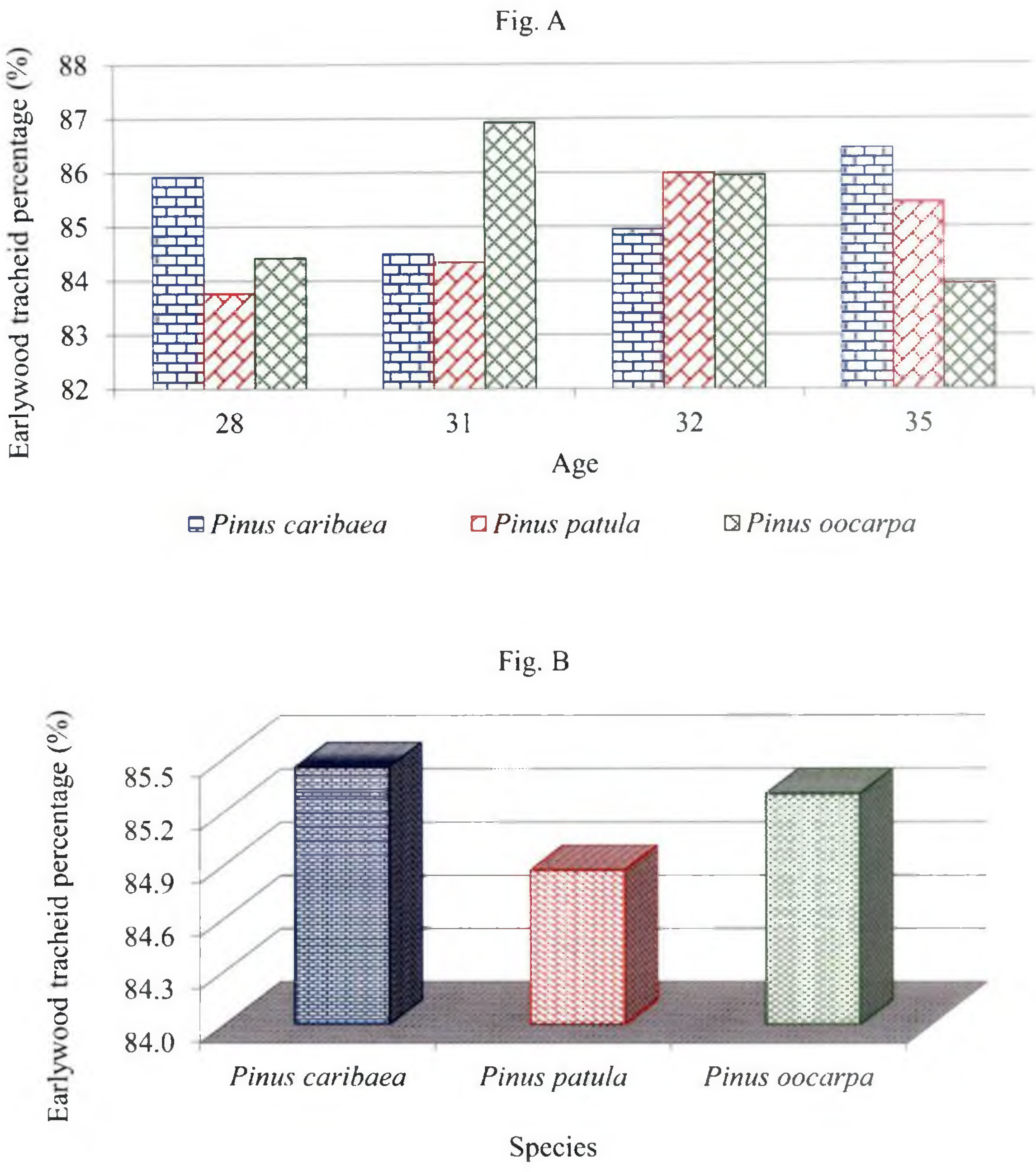

Fig. 51. Variation in earlywood tracheid percentage between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

The species mean on earlywood tracheid percentage averaged over all ages showed no significant difference among the three pines (Table 50). From Figure 51B it can be found that *Pinus patula* had the lowest value (84.87 %) and *Pinus caribaea* had the highest value (85.45 %). However, *Pinus oocarpa* (85.30 %) had a moderate value for earlywood tracheid percentage.

4.2.4.1b Variation due to position in a species within an age group

Results pertaining to variation in earlywood tracheid percentage between positions in a species within an age group is summarized in Table 51 and Figure 52. Analysis of variance shows that there is no statistically significant difference between the three radial positions within an age group.

In 28 years old plantation, except *Pinus patula* other two pine species had an increase in earlywood tracheid percentage from pith to periphery. The values ranged from 85.19 per cent to 86.89 per cent in *Pinus caribaea* and 83.81 per cent to 85.01 per cent in *Pinus oocarpa.* In the case of *Pinus patula*, values ranged from 85.54 per cent at pith, 81.23 per cent at middle and 84.53 per cent at periphery position. The results are illustrated in Figure 52A.

The radial distribution pattern showed an increasing trend from pith to periphery with respect to earlywood tracheid percentage in *Pinus patula* and *Pinus oocarpa* belonging to 31 years old plantation (Fig. 52B). The values ranged from 83.94 per cent to 85.10 per cent in *Pinus patula* and 85.84 per cent to 88.33 per cent in *Pinus oocarpa.* In the case of *Pinus caribaea*, values ranged from 85.52 per cent at pith, 83.88 per cent at middle and 84.07 per cent at periphery position.

The earlywood tracheid percentage of the three pine species, belonging to 32 years old plantation, at each radial position is graphically illustrated in Figure 52C.

Table 51. Mean earlywood tracheid percentage at pith, middle and periphery of pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Earlywood tracheid percentage (%)		
28	*Pinus caribaea*	85.19 (3.14)	85.68 (2.16)	86.89 (1.27)
	Pinus patula	85.54 (4.03)	81.23 (9.50)	84.53 (0.81)
	Pinus oocarpa	83.81 (0.69)	84.41 (1.68)	85.01 (2.50)
31	*Pinus caribaea*	85.52 (1.29)	83.88 (2.91)	84.07 (3.05)
	Pinus patula	83.94 (1.00)	83.96 (1.18)	85.10 (1.80)
	Pinus oocarpa	85.84 (2.08)	86.60 (1.61)	88.33 (1.35)
32	*Pinus caribaea*	84.94 (2.18)	84.45 (2.40)	85.41 (1.91)
	Pinus patula	87.25 (1.86)	84.01 (6.09)	86.65 (0.95)
	Pinus oocarpa	87.37 (2.35)	85.23 (2.62)	85.20 (2.71)
35	*Pinus caribaea*	86.58 (1.54)	85.75 (0.94)	87.03 (1.27)
	Pinus patula	85.92 (1.28)	85.07 (0.61)	85.30 (2.85)
	Pinus oocarpa	84.05 (2.98)	82.12 (1.30)	85.66 (3.08)
F value	0.40^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a row

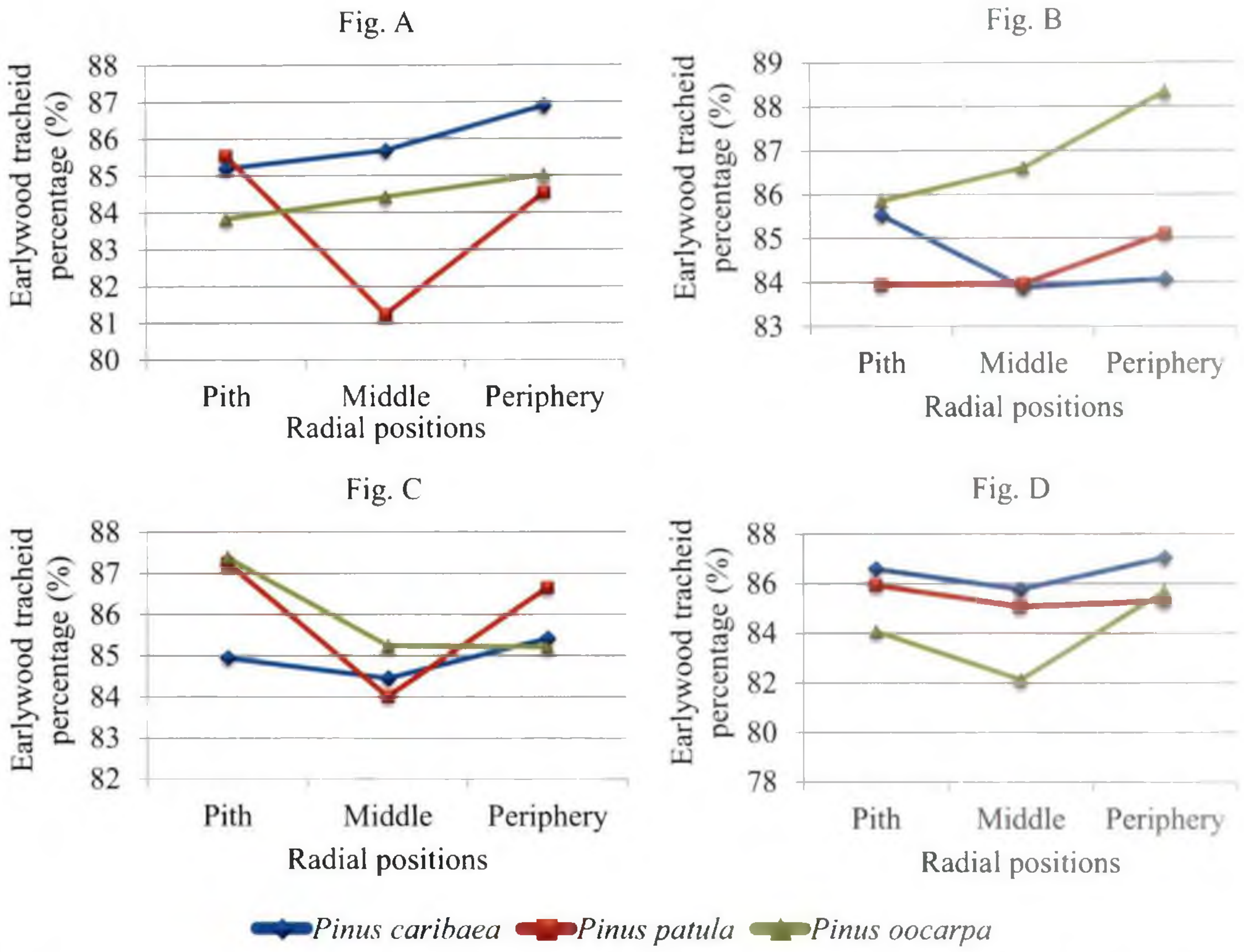

Fig. 52. Radial variation of earlywood tracheid percentage in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

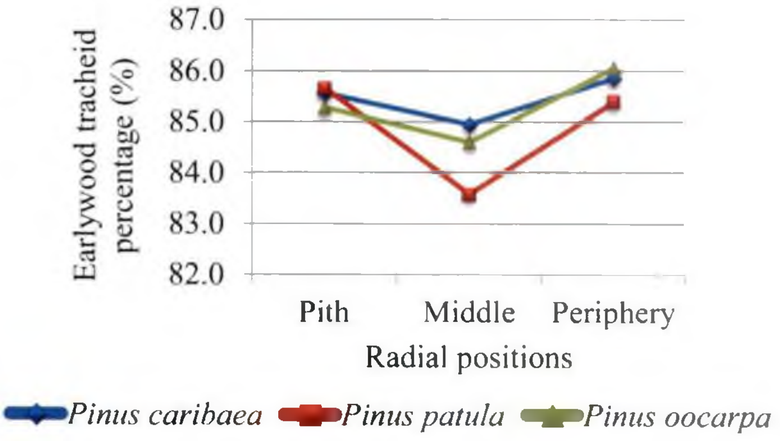

Fig. 53. Radial variation in mean earlywood tracheid percentage of pine species averaged over all ages

From this, it can found out that *Pinus caribaea* and *Pinus patula* showed lowest value at middle positions, whereas *Pinus oocarpa* had lowest value at periphery. *Pinus caribaea* had values that ranging from 84.45 per cent (middle) to 85.41 per cent (periphery) and in *Pinus patula*, it ranged from 84.01 per cent (middle) to 87.25 per cent (pith). On the other hand, in *Pinus oocarpa*, the values were found to range from 85.20 per cent (periphery) to 87.37 per cent (pith).

In 35 years old plantation, all the three pine species showed lowest values in earlywood tracheid percentage at the middle position. *Pinus caribaea* had values that ranged from 85.75 per cent (middle) to 87.03 per cent (periphery) and in *Pinus patula*, it varied from 85.07 per cent (middle) to 85.92 per cent (pith). Compared to this in *Pinus oocarpa*, the values ranged from 82.12 per cent at middle to 85.66 per cent at periphery position.

4.2.4.1c Variation due to position within species averaged across all ages

Results of analysis of variance conducted showed no significant variation in earlywood tracheid percentage with respect to position within each species averaged across all ages. Species mean averaged across all the ages in different radial positions are presented in Table 52 and Figure 53.

It can be seen that values were found to show no definite pattern of variation along the radial positions. None the less, all the three species had lowest value for earlywood tracheid percentage at the middle position. *Pinus patula* had values that ranged from 83.57 per cent (middle) to 85.66 per cent (periphery). On the other hand, both *Pinus caribaea* and *Pinus oocarpa* had higher values at the periphery position. In these species, values were found to range from 84.94 per cent to 85.85 per cent (*Pinus caribaea*) and 84.59 per cent to 86.05 per cent (*Pinus oocarpa*).

Table 52. Mean earlywood tracheid percentage in pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Earlywood tracheid percentage (%)		
Pith	85.56 (1.95)	85.66 (2.36)	85.27 (2.4)
Middle	84.94 (2.07)	83.57 (5.07)	84.59 (2.33)
Periphery	85.85 (2.13)	85.39 (1.73)	86.05 (2.55)
F value	1.05^{ns} (for comparing between position within a species)		

ns - non significant; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.2.4.2 Ray percentage in earlywood

4.2.4.2a Variation due to age and species

Results of analysis of variance showed that the interaction between age and species is not significant with respect to earlywood ray percentage. Species mean across all ages was also found to be non significant among the three pine species. The results are presented in Table 53 and Figure 54.

From Table 53, it can be seen that, in the 28 years old plantation, the earlywood ray percentage was found to range from 14.08 per cent (*Pinus caribaea*) to 16.24 per cent (*Pinus patula*). In the 31 years old plantation it ranged from 13.08 per cent (*Pinus oocarpa*) 15.64 per cent (*Pinus patula*) and in the 32 years old plantation it ranged from 14.03 per cent (*Pinus patula*) to 15.06 per cent (*Pinus caribaea*). In the 35 years old plantation, earlywood ray percentage ranged from 13.55 per cent (*Pinus caribaea*) to 16.06 per cent (*Pinus oocarpa*). The results are illustrated graphically in Figure 54A.

Table 53. Mean earlywood ray percentage in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Earlywood ray percentage (%)				
Pinus caribaea	14.08 (2.15)	15.51 (2.34)	15.06 (1.93)	13.55 (1.24)	14.55 (2.03)
Pinus patula	16.24 (5.53)	15.64 (1.29)	14.03 (3.55)	14.57 (1.64)	15.12 (3.41)
Pinus oocarpa	15.59 (1.63)	13.08 (1.85)	14.06 (2.47)	16.06 (2.71)	14.70 (2.43)
F value	1.97^{ns} (for comparing between age and species) 0.42^{ns} (for comparing species averaged over all ages)				

ns - non significant; values within parentheses is standard deviation

In *Pinus caribaea*, the values on earlywood ray percentage was found to range from 13.55 per cent (35 years old plantation) to 15.51 per cent (31years old plantation) and in *Pinus patula* it ranged from 14.03 per cent (32 years old plantation) to 16.24 per cent (28 years old plantation). On the other hand, in *Pinus oocarpa,* earlywood ray percentage was found to range from 13.08 per cent (31 years old plantation) to 16.06 per cent (35 years old plantation) (Fig. 54A)

The species mean on earlywood ray percentage averaged over all ages showed no significant difference among the three pines (Table 53). From Figure 54B it can be found that *Pinus patula* had the highest value (15.12 %) and *Pinus caribaea* had the lowest value (14.55 %). However, *Pinus oocarpa* (14.70 %) had a moderate value for earlywood ray percentage.

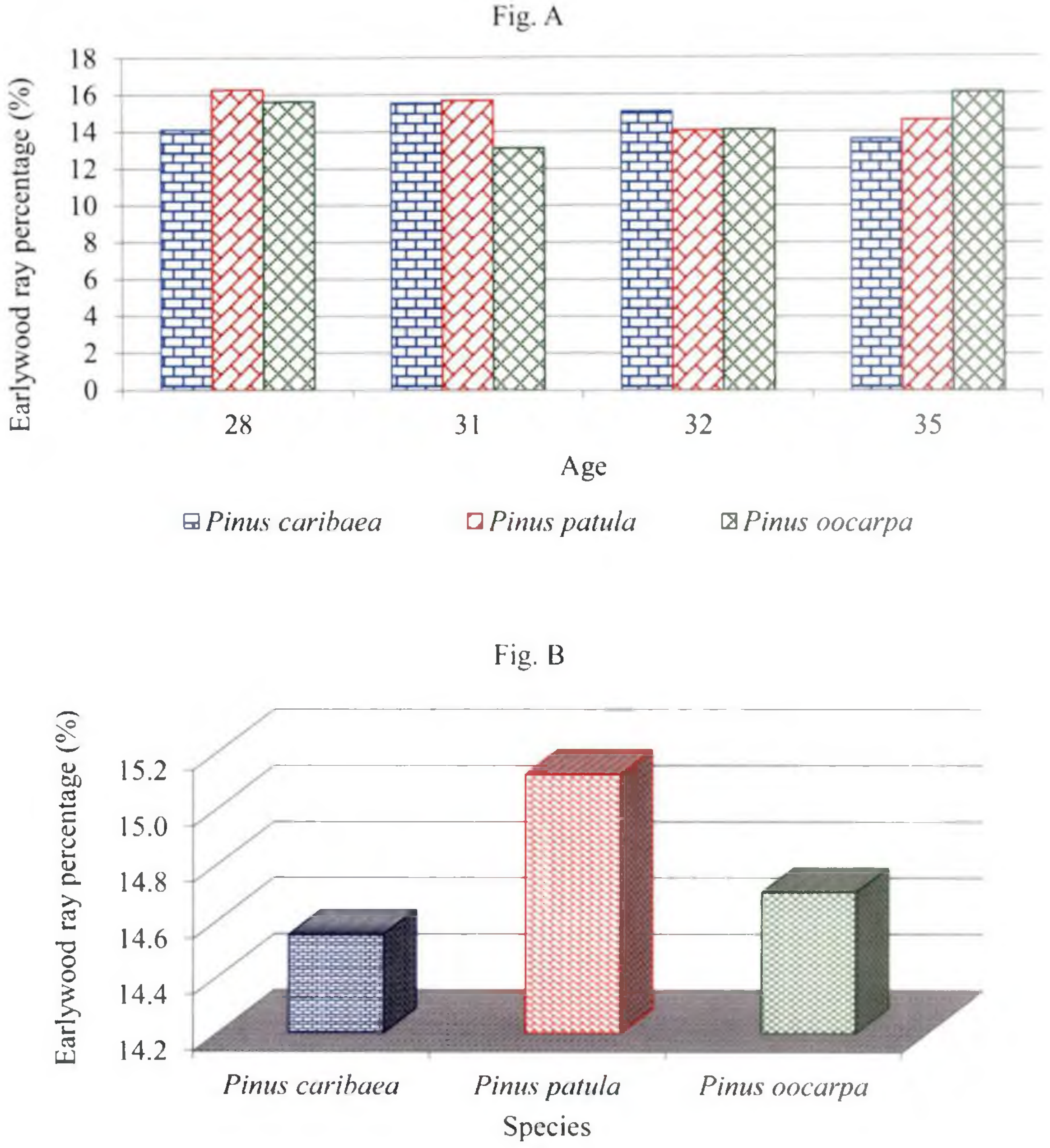

Fig. 54. Variation in earlywood ray percentage between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

4.2.4.2b Variation due to position in a species within an age group

Results pertaining to variation in earlywood ray percentage between positions in a species within an age group is summarized in Table 54 and Figure 55. Analysis of variance shows that there is no statistically significant difference between the three radial positions within an age group.

In 28 years old plantation, except *Pinus patula* the other two pine species had a decrease in earlywood ray percentage from pith to periphery. The values ranged from 14.81 per cent to 13.11 per cent in *Pinus caribaea* and 16.19 per cent to 14.99 per cent in *Pinus oocarpa.* In the case of *Pinus patula*, values ranged from 14.46 per cent at pith, 18.77 per cent at middle and 15.47 per cent at periphery position. The results are illustrated in Figure 55A.

The radial distribution pattern showed a decreasing trend from pith to periphery with respect to earlywood ray percentage in *Pinus oocarpa* belonging to 31 years old plantation (Fig. 55B). The values ranged from 11.67 per cent to 14.16 per cent in *Pinus oocarpa.* In the case of *Pinus caribaea*, values ranged from 14.48 per cent at pith, 16.12 per cent at middle and 15.93 per cent at periphery position. On the other hand in *Pinus patula* values ranged from 15.97 at pith, 16.04 at middle and 14.90 at periphery.

Earlywood ray percentage of the three pine species, belonging to 32 years old plantation at each radial position is graphically illustrated in Figure 55C. *Pinus caribaea* had values that ranged from 14.59 per cent (periphery) to 15.55 per cent (middle) and in *Pinus patula*, it ranged from 12.75 per cent (pith) to 15.99 per cent (middle). On the other hand, in *Pinus oocarpa,* the values were found to range from 12.63 per cent (pith) to 14.80 per cent (periphery).

Table 54. Mean earlywood ray percentage at pith, middle and periphery of pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Earlywood ray percentage (%)		
28	*Pinus caribaea*	14.81 (3.14)	14.32 (2.16)	13.11 (1.27)
	Pinus patula	14.46 (4.03)	18.77 (9.50)	15.47 (0.81)
	Pinus oocarpa	16.19 (0.69)	15.59 (1.68)	14.99 (2.50)
31	*Pinus caribaea*	14.48 (1.29)	16.12 (2.91)	15.93 (3.05)
	Pinus patula	15.97 (0.91)	16.04 (1.18)	14.90 (1.80)
	Pinus oocarpa	14.16 (2.08)	13.40 (1.61)	11.67 (1.35)
32	*Pinus caribaea*	15.06 (2.18)	15.55 (2.40)	14.59 (1.91)
	Pinus patula	12.75 (1.86)	15.99 (6.09)	13.35 (0.95)
	Pinus oocarpa	12.63 (2.35)	14.77 (2.62)	14.80 (2.71)
35	*Pinus caribaea*	13.42 (1.54)	14.25 (0.94)	12.97 (1.27)
	Pinus patula	14.08 (1.28)	14.93 (0.61)	14.70 (2.85)
	Pinus oocarpa	15.95 (2.98)	17.88 (1.30)	14.34 (3.08)
F value	0.40^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

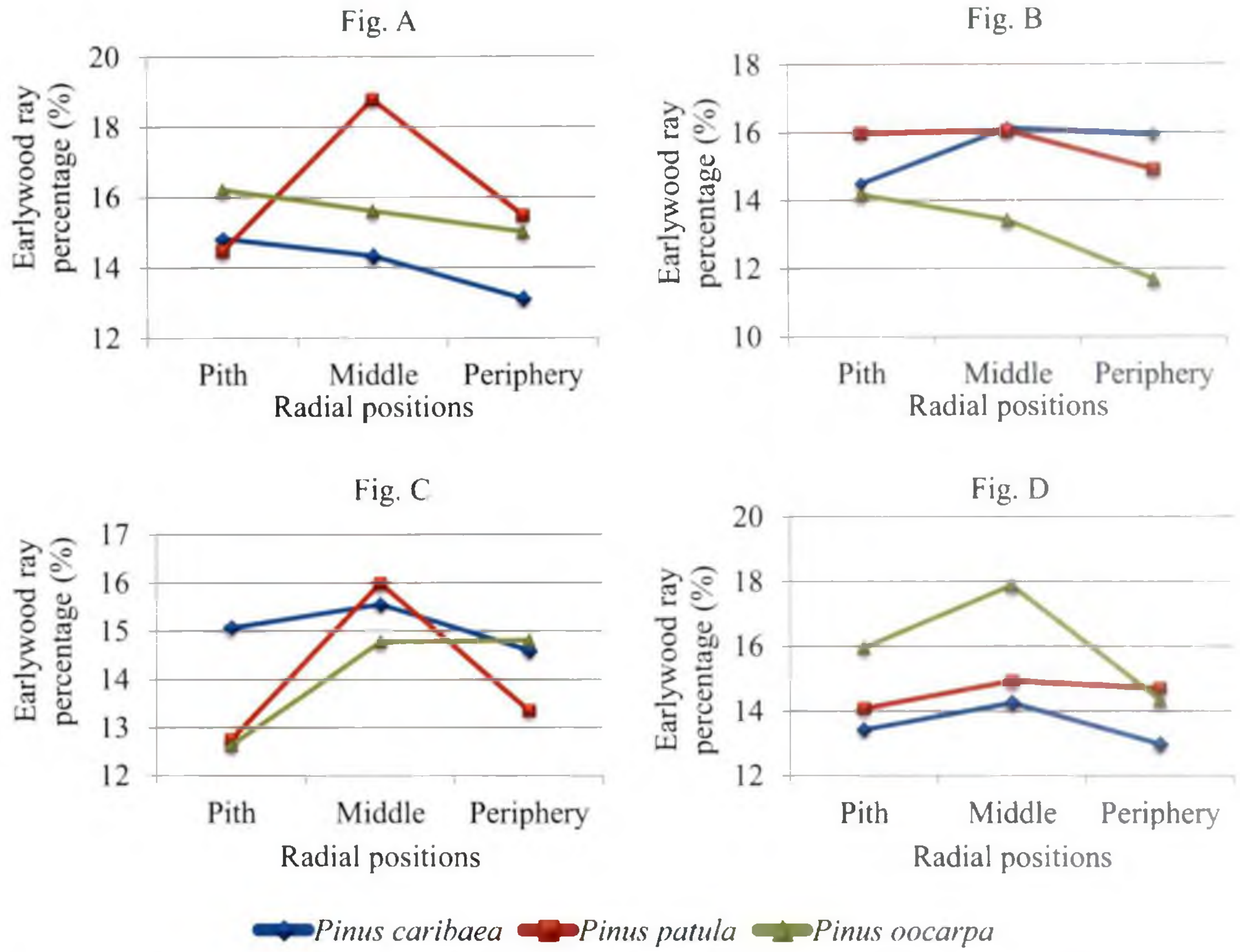

Fig. 55. Radial variation of earlywood ray percentage in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

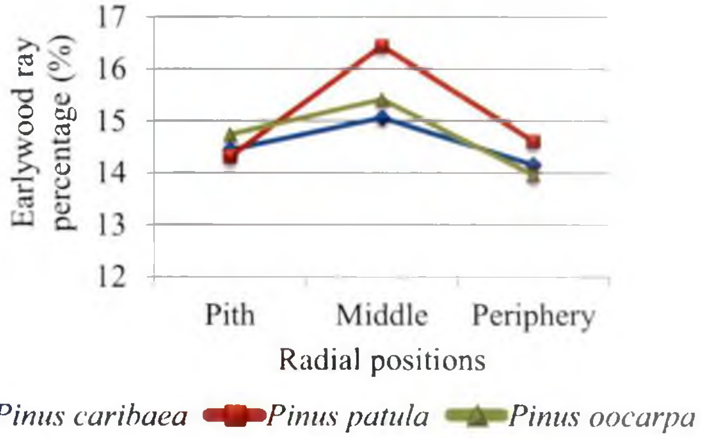

Fig. 56. Radial variation in mean earlywood tracheid percentage of pine species averaged over all ages

In 35 years old plantation, all the three pine species showed highest values in earlywood ray percentage at middle position. *Pinus caribaea* had values that ranged from 12.97 per cent (periphery) to 14.25 per cent (middle) and in *Pinus patula*, it varied from 14.08 per cent (pith) to 14.93 per cent (middle). On the other hand in *Pinus oocarpa*, the values ranged from 14.34 per cent at periphery to 17.88 per cent at middle position (Fig. 55D).

4.2.4.2c Variation due to position within species averaged across all ages

Results of analysis of variance conducted showed no significant variation in earlywood ray percentage with respect to position within each species averaged across all ages. Species mean averaged across all the ages in different radial positions are presented in Table 55 and Figure 56.

Table 55. Mean earlywood ray percentage in pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Earlywood ray percentage (%)		
Pith	14.44 (1.95)	14.31 (2.34)	14.73 (2.40)
Middle	15.06 (2.07)	16.44 (5.07)	15.41 (2.33)
Periphery	14.15 (2.13)	14.61 (1.73)	13.95 (2.55)
F value	1.06^{ns} (for comparing between position within a species)		

ns - non significant; values within parentheses is standard deviation

It can be seen that values were found to show no definite pattern of variation along the radial positions. All the three species had highest value for earlywood ray percentage at the middle position. *Pinus patula* had values that ranged from 14.31 per cent (pith) to 16.44 per cent (middle). On the other hand, both *Pinus caribaea* and *Pinus oocarpa* had lower values at the periphery position. In them, values were found to range from 14.15 per cent to 15.06 per cent (*Pinus caribaea*) and 13.95 per cent to 15.41 per cent (*Pinus oocarpa*).

4.2.4.3 Tracheid percentage in latewood

4.2.4.3a Variation due to age and species

The data on variation in latewood tracheid percentage with respect to age and species is presented in Table 56 and Figure 57. Analysis of variance revealed that age and species interaction was found to be highly significant at 1 per cent variance level. However, species mean across all ages was found have no significant difference among the three pine species.

From Table 56, it can be seen that there is no significant variation between species within each age level except in 32 years old plantation. In the case of 28 years old plantation, *Pinus patula* (85.60 %) had the maximum latewood tracheid percentage followed by *Pinus oocarpa* (84.22 %) and *Pinus caribaea* (82.87 %). However, in 31 years old plantation *Pinus patula* (82.60 %) had the lowest value for latewood tracheid percentage followed by *Pinus oocarpa* (83.95 %) and *Pinus caribaea* (85.20 %). Similarly, in 35 years old plantation, *Pinus patula* (82.96 %) had the lowest value for latewood tracheid percentage followed by *Pinus oocarpa* (83.64 %) and *Pinus caribaea* (85.63 %). While in 32 years old plantation, *Pinus patula* (86.23 %) differed significantly from *Pinus caribaea* (83.08 %), while these two species were found to be homogenous with *Pinus oocarpa* (84.97 %). These values are illustrated graphically in Figure 57A.

Table 56. Mean latewood tracheid percentage in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Latewood tracheid percentage (%)				
Pinus caribaea	$82.87^{a\ A}$ (1.60)	$85.20^{a\ A}$ (1.47)	$83.08^{b\ A}$ (1.18)	$85.63^{a\ A}$ (1.23)	84.19 (1.82)
Pinus patula	$85.60^{a\ AB}$ (1.30)	$82.60^{a\ C}$ (1.40)	$86.23^{a\ A}$ (0.84)	$82.96^{a\ BC}$ (1.22)	84.35 (1.98)
Pinus oocarpa	$84.22^{a\ A}$ (1.71)	$83.95^{a\ A}$ (1.39)	$84.97^{ab\ A}$ (1.77)	$83.64^{a\ A}$ (0.99)	84.19 (1.52)
F value	8.28** (for comparing between age and species) 0.10^{ns} (for comparing species averaged over all ages)				
C.D	2.86				

** Significant at 1 % level; ns non significant; C.D - critical difference; values within parentheses is standard deviation; means with same lower case letter as superscript in a column are homogeneous; means with same upper case letters as superscript in a row are homogeneous

From Table 56, it can be seen that except *Pinus patula*, the other two pine species did not show any variation in latewood tracheid percentage within species at different age levels. The mean values did not show any specific pattern of variation within species at different age levels (Fig. 57A). In *Pinus caribaea*, the latewood tracheid percentage values were found to range from 82.87 per cent (28 years old plantation) to 85.63 per cent (35years old plantation) and in *Pinus oocarpa* it ranged from 83.64 per cent (35 years old plantation) to 84.97 per cent (32 years old plantation). On the other hand, in *Pinus patula* 31 (82.60 %) and 32 (86.23 %) years old plantation were found to differ significantly from each other, while 31 (82.60 %) and 35 (82.96 %) years old plantations were found to be homogenous with each other. However 28 (85.60 %) and 32 (86.23 %) years old plantations were found to show no

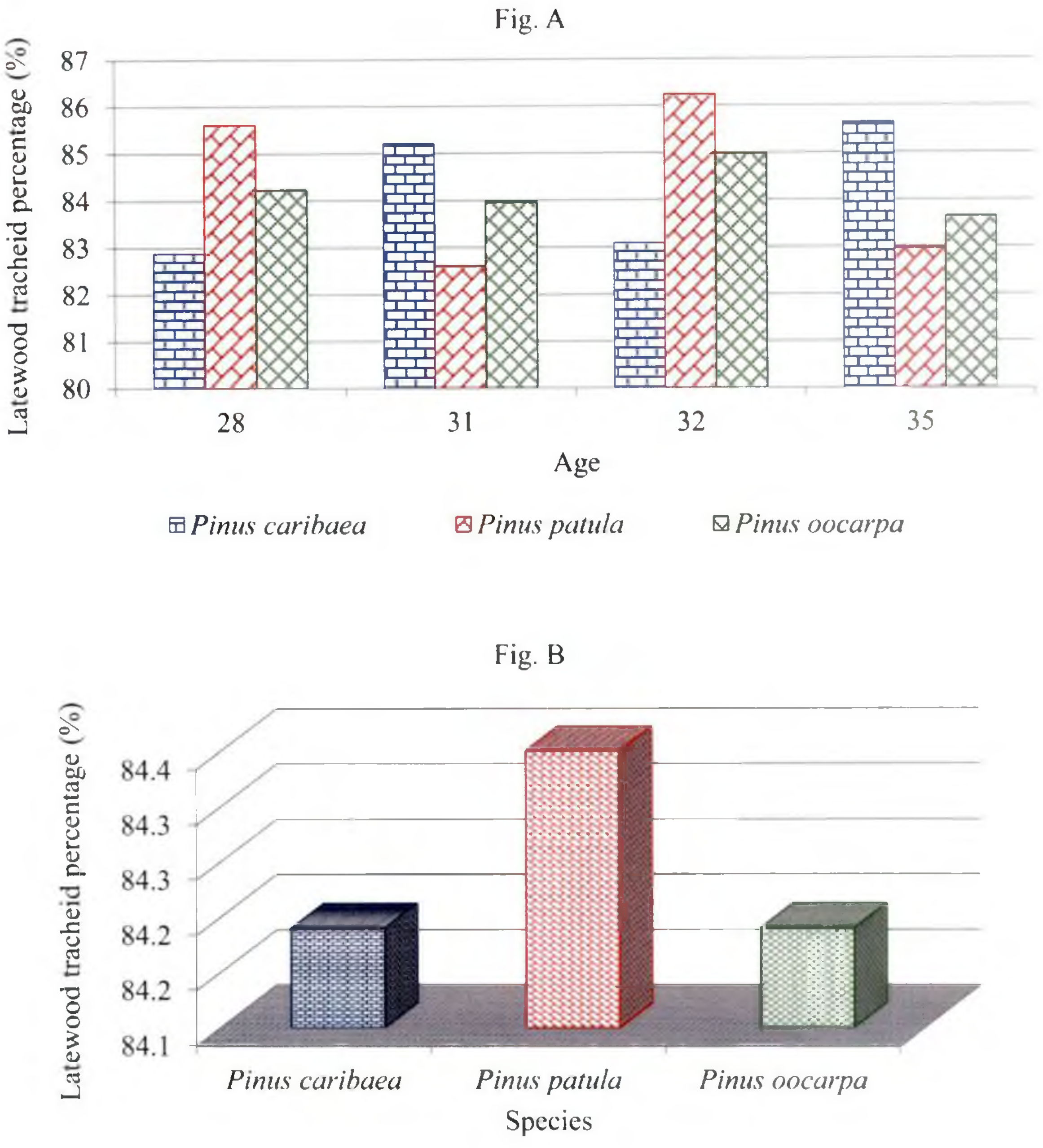

Fig. 57. Variation in latewood tracheid percentage between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

statistically significant difference in latewood tracheid percentage. Similarly, 35 (82.96 %) and 28 (85.60 %) years old plantations had homogenous values.

A comparison of latewood tracheid percentage averaged over all ages showed no significant difference between the three pine species that were studied. These mean values were illustrated graphically in Figure 57B. From this it can be seen that, both *Pinus caribaea* and *Pinus oocarpa* (84.19 %) had lower values and *Pinus patula* (84.35 %) was found to have higher value for latewood tracheid percentage.

4.2.4.3b Variation due to position in a species within an age group

The summarized results of mean latewood tracheid percentage among the three pine species belonging to different ages at different radial positions are presented in Table 57 and Figure 58. Analysis of variance revealed no significant variation between radial positions within the species at different age levels.

Figure 58A illustrates the radial latewood tracheid percentage values of pine species belonging to 28 years old plantation. It shows no particular pattern radially. In *Pinus caribaea,* the latewood tracheid percentage values were found to range from 81.75 per cent (pith) to 84.73 per cent (periphery) and in *Pinus patula*, it ranged from 84.26 per cent (middle) to 86.44 per cent (periphery), whereas in *Pinus oocarpa*, values were found to range from 83.84 per cent (periphery) to 84.56 per cent (pith).

In 31 years old plantation, *Pinus caribaea* had higher value for latewood tracheid percentage at pith (85.54 %) and lowest value at middle (84.53 %) position, whereas *Pinus patula* had higher value at pith (83.60 %) and lowest value at periphery (81.46 %) position. Similarly, *Pinus oocarpa* was found to have highest value at pith (84.18 %) and lowest value at middle (83.79 %) position. These results are illustrated in Figure 58B.

Table 57. Mean latewood tracheid percentage at pith, middle and periphery of pine species belonging to different ages

Age	**Species**	**Radial positions**		
		Pith	**Middle**	**Periphery**
		Latewood tracheid percentage (%)		
28	*Pinus caribaea*	81.75 (0.43)	82.12 (0.71)	84.73 (1.30)
	Pinus patula	86.11 (0.95)	84.26 (0.59)	86.44 (1.15)
	Pinus oocarpa	84.56 (1.87)	84.24 (2.36)	83.84 (1.53)
31	*Pinus caribaea*	85.54 (1.40)	84.53 (1.28)	85.53 (2.02)
	Pinus patula	83.60 (1.15)	82.75 (1.05)	81.46 (1.40)
	Pinus oocarpa	84.18 (0.74)	83.79 (0.74)	83.90 (2.55)
32	*Pinus caribaea*	82.93 (0.83)	82.21 (0.86)	84.09 (1.18)
	Pinus patula	86.83 (1.21)	85.69 (0.39)	86.17 (0.48)
	Pinus oocarpa	85.13 (2.48)	84.28 (1.93)	85.50 (1.25)
35	*Pinus caribaea*	84.34 (0.91)	86.29 (0.50)	86.27 (1.07)
	Pinus patula	82.29 (0.38)	82.59 (1.23)	84.02 (1.32)
	Pinus oocarpa	83.78 (1.79)	83.20 (0.40)	83.94 (0.35)
F value	1.70^{ns} (for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

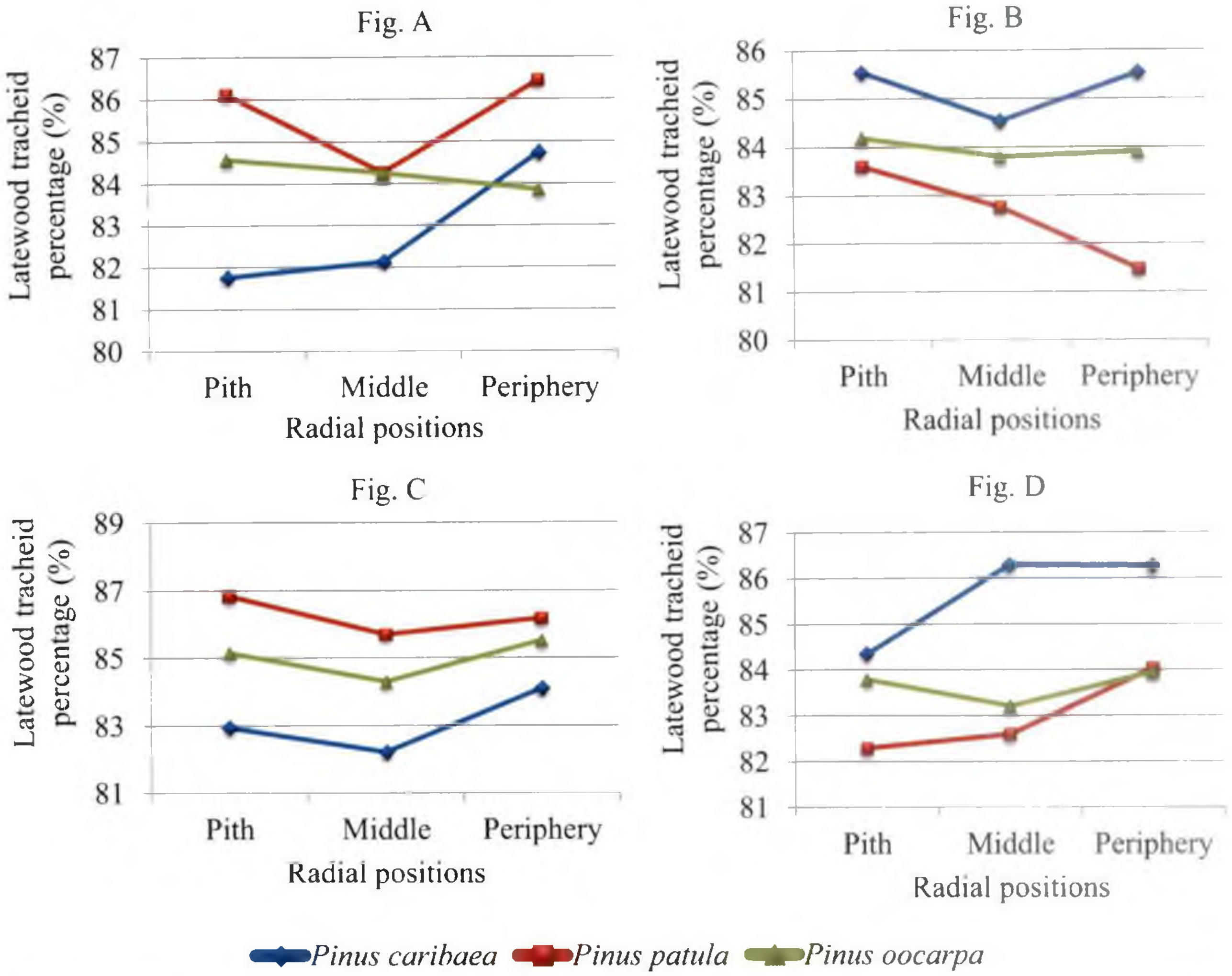

Fig. 58. Radial variation of latewood tracheid percentage in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

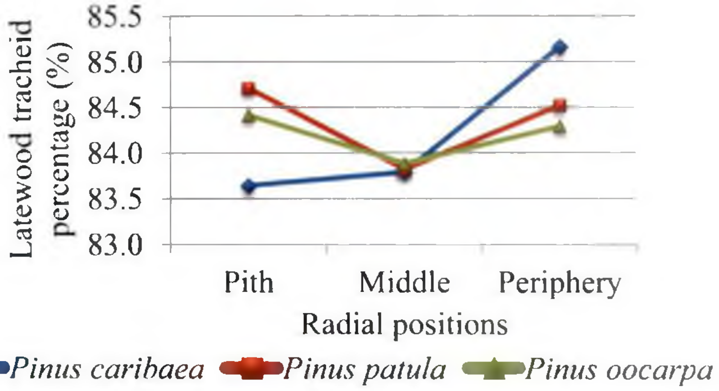

Fig. 59. Radial variation in mean latewood tracheid percentage of pine species averaged over all ages

Latewood tracheid percentage in the three pine species belonging to 32 years old plantation is illustrated radially in Figure 58C. It shows that all the three species were found to have lowest value for latewood tracheid percentage at middle position. The values were found to range from 82.21 per cent (middle) to 84.09 per cent (periphery) in *Pinus caribaea,* whereas in *Pinus patula*, values were found to range from 85.69 per cent (middle) to 86.83 per cent (pith) and in *Pinus oocarpa*, it ranged from 84.28 per cent (middle) to 85.50 per cent (periphery).

The mean latewood tracheid percentage at radial positions of the three pine species belonging to 35 years old plantation is illustrated in Figure 58D. In *Pinus caribaea*, values ranged from 84.34 per cent (pith) to 86.29 per cent (middle) and in *Pinus oocarpa*, it ranged from 83.20 per cent (middle) to 83.94 per cent (periphery). On the other hand, *Pinus patula* showed an increasing pattern in values from pith (82.29 %) to periphery (84.02 %).

4.2.4.3c Variation due to position within species averaged across all ages

Analysis of variance reveals that mean latewood tracheid percentage in three pine species at different radial positions averaged over all ages was found to have highly significant difference at 1 per cent variance level. These results are summarized in Table 58.

Figure 59, illustrates the radial variation which shows no definite pattern within the species. In *Pinus caribaea*, values at pith (83.64 %) and middle (83.79 %) were found to be homogenous with each other, while these two radial positions differed significantly from periphery (85.16 %). In *Pinus patula*, pith (84.71 %) differed significantly from middle (83.82 %) position, while these two radial positions were found to be homogenous with periphery (84.52 %). Compared to this, *Pinus oocarpa* had no significant difference among the radial positions. In this species the value was found to range from 83.88 per cent (middle) to 84.41 per cent (pith).

Table 58. Mean latewood tracheid percentage in three pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Latewood tracheid percentage (%)		
Pith	83.64^{b} (1.70)	84.71^{a} (2.10)	84.41^{a} (1.64)
Middle	83.79^{b} (1.97)	83.82^{b} (1.51)	83.88^{a} (1.42)
Periphery	85.16^{a} (1.50)	84.52^{ab} (2.31)	84.29^{a} (1.56)
F value	3.61** (for comparing between position within a species)		
C.D	0.88 (for comparing between position within a species)		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

4.2.4.4 Ray percentage in latewood

4.2.4.4a Variation due to age and species

The data on variation in latewood ray percentage with respect to age and species is presented in Table 59 and Figure 60. Analysis of variance revealed that age and species interaction was found to be highly significant at 1 per cent variance level. However, species mean across all ages was found have no significant difference among the three pine species.

From Table 59, it can be seen that there is no significant variation between species within each age levels except in 32 years old plantation. In the case of

28 years old plantation, *Pinus patula* (14.40 %) had the lowest latewood ray percentage followed by *Pinus oocarpa* (15.78 %) and *Pinus caribaea* (17.13 %). However, in 31 years old plantation *Pinus patula* (17.40 %) had the highest value for latewood ray percentage followed by *Pinus oocarpa* (16.05 %) and *Pinus caribaea* (14.80 %). Similarly in 35 years old plantation, *Pinus patula* (17.04 %) had the highest value for latewood ray percentage followed by *Pinus oocarpa* (16.36 %) and *Pinus caribaea* (14.37 %). While in 32 years old plantation, *Pinus patula* (13.77 %) differed significantly from *Pinus caribaea* (16.92 %), while these two species were found to be homogenous with *Pinus oocarpa* (15.03 %). These values are illustrated graphically in Figure 60A.

Table 59. Mean latewood ray percentage in pine species at different ages

Species	**Age in years**				**Mean**
	28	**31**	**32**	**35**	
	Latewood ray percentage (%)				
Pinus caribaea	17.13$^{a\ A}$ (1.60)	14.80$^{a\ A}$ (1.47)	16.92$^{a\ A}$ (1.18)	14.37$^{a\ A}$ (1.23)	15.81 (1.82)
Pinus patula	14.40$^{a\ BC}$ (1.30)	17.40$^{a\ A}$ (1.40)	13.77$^{b\ C}$ (0.84)	17.04$^{a\ AB}$ (1.22)	15.65 (1.98)
Pinus oocarpa	15.78$^{a\ A}$ (1.71)	16.05$^{a\ A}$ (1.39)	15.03$^{ab\ A}$ (1.77)	16.36$^{a\ A}$ (0.99)	15.81 (1.52)
F value	8.28** (for comparing between age and species) 0.10^{ns} (for comparing species averaged over all ages)				
C.D	2.86				

** Significant at 1 % level; C.D - critical difference; ns non significant; values within parentheses is standard deviation; means with same lower case letter as superscript in a column are homogeneous; means with same upper case letters as superscript in a row are homogeneous

From Table 59, it can be seen that except *Pinus patula*, the other two pine species did not show any variation in latewood ray percentage within species at

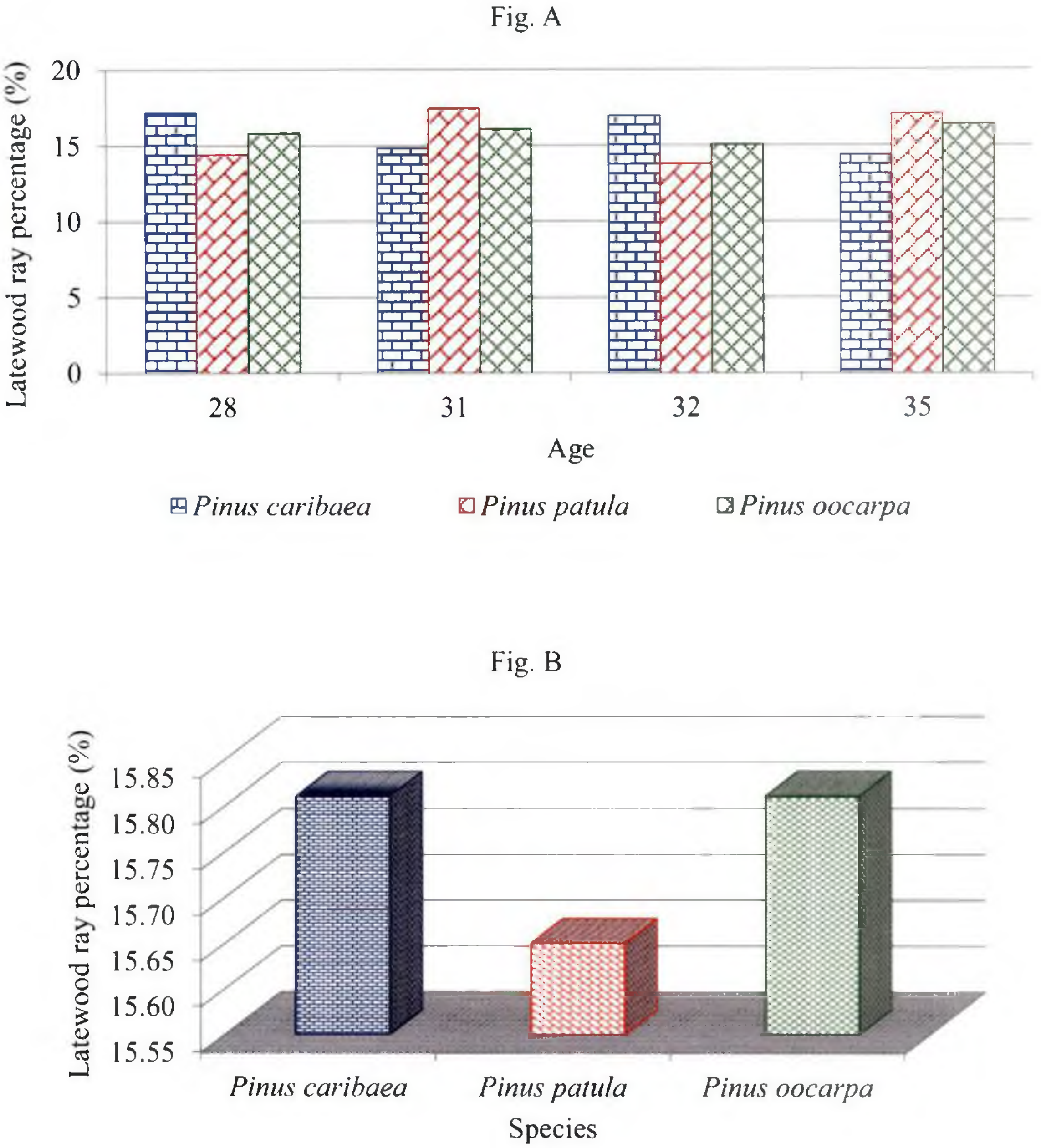

Fig. 60. Variation in latewood ray percentage between selected tropical pine species: (A) due to age and species interactions; (B) between species averaged over all ages

different age levels. Figure 60A shows no specific pattern of variation within species at different age levels. In *Pinus caribaea* however, the latewood tracheid percentage values were found to range from 14.37 per cent (35 years old plantation) to 17.13 per cent (28 years old plantation) and in *Pinus oocarpa* it ranged from 15.03 per cent (32 years old plantation) to 16.36 per cent (35 years old plantation). On the other hand, in *Pinus patula* 31 (17.40 %) and 32 (13.77 %) years old plantation were found to differ significantly from each other, while 31 (17.40 %) and 35 (17.04 %) years old plantations were found to be homogenous with each other. Compared to this, 28 (14.40 %) and 32 (13.77 %) years old plantations were found to show no statistically significant difference in latewood tracheid percentage. Similarly, 35 (17.04 %) and 28 (14.40 %) years old plantations had homogenous values.

A comparison of latewood tracheid percentage averaged over all ages showed no significant difference between the three pine species that were studied. These mean values were illustrated graphically in Figure 60B. From this, it can be seen that, both *Pinus caribaea* and *Pinus oocarpa* (15.81 %) had higher values and *Pinus patula* (15.65 %) was found to have lowest value for latewood ray percentage.

4.2.4.4b Variation due to position in a species within an age group

The summarized results of mean latewood ray percentage among the three pine species belonging to different ages at different radial positions are presented in Table 60 and Figure 61. Analysis of variance revealed no significant variation between radial positions within the species at different age levels.

Figure 61A illustrates the radial latewood ray percentage values of pine species belonging to 28 years old plantation. It shows no particular pattern radially. In *Pinus caribaea,* the latewood tracheid percentage values were found to range from 15.27 per cent (periphery) to 18.25 per cent (pith) and in *Pinus patula*, it ranged from

Table 60. Mean latewood ray percentage at pith, middle and periphery of pine species belonging to different ages

Age	Species	Radial positions		
		Pith	Middle	Periphery
		Latewood ray percentage (%)		
28	*Pinus caribaea*	18.25 (0.43)	17.88 (0.71)	15.27 (1.30)
	Pinus patula	13.89 (0.95)	15.74 (0.59)	13.56 (1.15)
	Pinus oocarpa	15.44 (1.87)	15.76 (2.36)	16.16 (1.53)
31	*Pinus caribaea*	14.46 (1.40)	15.47 (1.28)	14.47 (2.02)
	Pinus patula	16.40 (1.15)	17.25 (1.05)	18.54 (1.40)
	Pinus oocarpa	15.82 (0.74)	16.21 (0.74)	16.10 (2.55)
32	*Pinus caribaea*	17.07 (0.83)	17.79 (0.86)	15.91 (1.18)
	Pinus patula	13.17 (1.21)	14.31 (0.39)	13.83 (0.48)
	Pinus oocarpa	14.87 (2.48)	15.72 (1.93)	14.50 (1.25)
35	*Pinus caribaea*	15.66 (0.91)	13.71 (0.50)	13.73 (1.07)
	Pinus patula	17.71 (0.38)	17.41 (1.23)	15.98 (1.32)
	Pinus oocarpa	16.22 (1.79)	16.80 (0.40)	16.06 (0.35)
F value	1.70^{ns}(for comparing between age and position within species)			

ns - non significant; values within parentheses is standard deviation

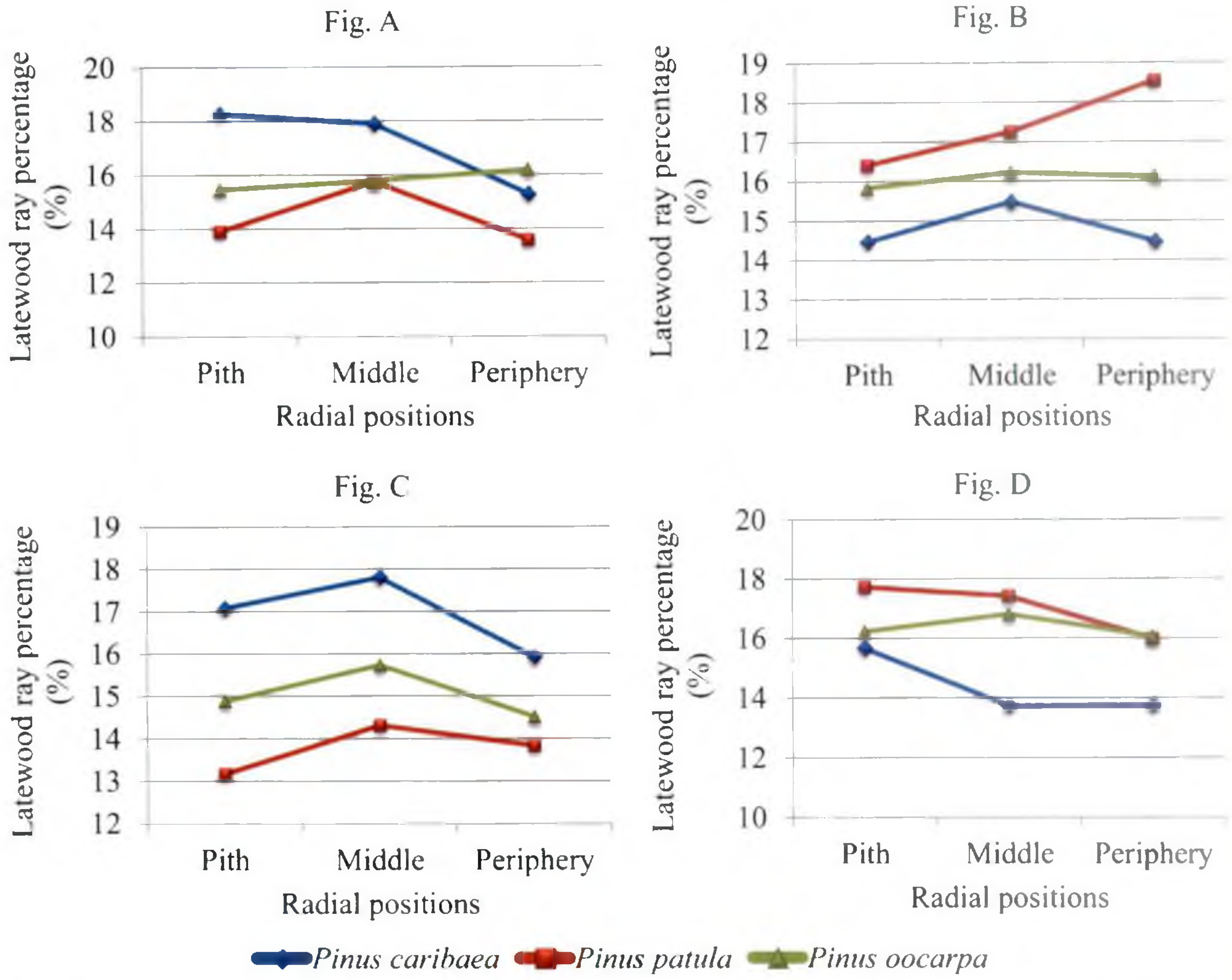

Fig. 61. Radial variation of latewood ray percentage in pine species belonging to different ages: (A) 28 years; (B) 31 years; (C) 32 years; (D) 35 years

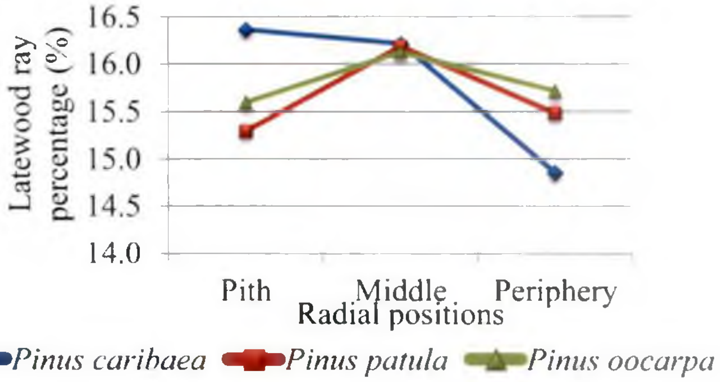

Fig. 62. Radial variation in mean latewood ray percentage of pine species averaged over all ages

13.56 per cent (periphery) to 15.74 per cent (middle). On the other hand in *Pinus oocarpa*, values were found to range from 15.44 per cent (pith) to 16.16 per cent (periphery).

In 31 years old plantation, *Pinus caribaea* had lower value for latewood ray percentage at pith (14.46 %) and higher value at middle (15.47 %) position, whereas *Pinus patula* had lowest value at pith (16.40 %) and higher value at periphery (18.54 %) position. Similarly, *Pinus oocarpa* was found to have lowest value at pith (15.82 %) and highest value at middle (16.21 %) position. These results are illustrated in Figure 61B.

Latewood ray percentage in the three pine species belonging to 32 years old plantation is illustrated radially in Figure 61C. It shows that both *Pinus caribaea* and *Pinus oocarpa* were found to have lowest value for latewood ray percentage at periphery, whereas *Pinus patula* had lowest value at pith. The values were found to range from 15.91 per cent (periphery) to 17.79 per cent (middle) in *Pinus caribaea*. In *Pinus patula*, values were found to range from 13.17 per cent (pith) to 14.31 per cent (middle) and in *Pinus oocarpa*, it ranged from 14.50 per cent (periphery) to 15.72 per cent (middle).

The mean latewood tracheid percentage at radial positions of three pine species belonging to 35 years old plantation is illustrated in Figure 61D. In *Pinus caribaea*, values ranged from 13.71 per cent (middle) to 15.66 per cent (pith) and in *Pinus oocarpa*, it ranged from 16.06 per cent (periphery) to 16.80 per cent (middle). On the other hand, *Pinus patula* showed an increasing pattern in values from periphery (15.98 %) to pith (17.71 %).

4.2.4.4c Variation due to position within species averaged across all ages

Analysis of variance revealed that mean latewood ray percentage in three pine species at different radial positions averaged over all ages was found to have highly significant difference at 1 per cent variance level. These results are summarized in Table 61.

Table 61. Mean latewood ray percentage in pine species at different radial positions averaged over all ages

Radial positions	**Species**		
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***
	Latewood ray percentage (%)		
Pith	16.36^a (1.70)	15.29^b (2.10)	15.59^a (1.64)
Middle	16.21^a (1.97)	16.18^a (1.51)	16.12^a (1.42)
Periphery	14.85^b (1.50)	15.48^{ab} (2.31)	15.71^a (1.56)
F value	3.61** (for comparing between position within a species)		
C.D	0.88(for comparing between position within a species)		

** Significant at 1 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous within a column

Figure 62, illustrates the radial variation which shows no definite pattern within the species. In *Pinus caribaea*, values at pith (16.36 %) and middle (16.21 %) were found to be homogenous with each other, while these two radial positions differed significantly from periphery (14.85 %). In *Pinus patula*, pith (15.29 %) differed significantly from middle (16.18 %) position, while these two radial positions were found to be homogenous with periphery (15.48 %). Compared to this, *Pinus oocarpa* had no significant difference among the radial positions. In this species the values were found to range from 15.59 per cent (pith) to 16.12 per cent (middle).

4.3 CHEMICAL PROPERTIES

Results on variation in chemical properties of selected tropical pine species of 1975 pine plantation (35 years old) are presented in Table 62 and Figure 63.

Table 62. Mean cellulose content and lignin content of pine species belonging to 1975 plantation (35 years old)

Species	**Cellulose content (%)**	**Lignin content (%)**
Pinus caribaea	33.54^b (2.78)	29.54^a (1.12)
Pinus patula	40.32^b (4.85)	26.20^b (1.85)
Pinus oocarpa	47.55^a (2.09)	23.80^b (1.89)
F-value	12.41**	9.06*
C.D	6.89	3.32

** Significant at 1 % level; * Significant at 5 % level; C.D - critical difference; values within parentheses is standard deviation; means with same letter as superscript are homogenous

4.3.1 Cellulose content

The analysis of variance conducted revealed that species differ significantly with respect to cellulose content at 1 per cent level (Table 62). From the Table 62, it can be seen that cellulose content of *Pinus oocarpa* differs significantly from *Pinus caribaea* and *Pinus patula*. On the other hand, there is no significant difference between the cellulose content of *Pinus caribaea* and *Pinus patula*. Mean cellulose content was highest in *Pinus oocarpa* (47.55 %) and lowest in *Pinus caribaea* (33.54 %) (Fig. 63). *Pinus patula* had moderate values (40.32 %).

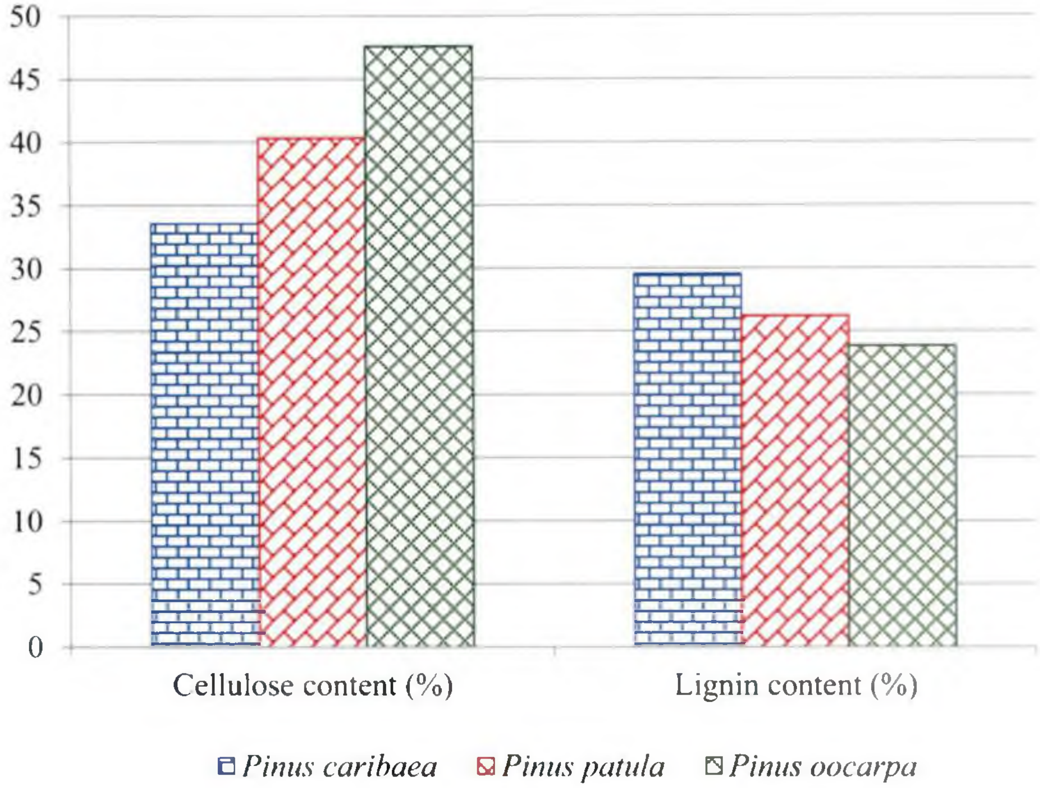

Fig. 63. Variation of cellulose and lignin content in selected tropical pine species belonging to 1975 plantation (35 years old)

4.3.2 Lignin content

Analysis of variance carried out revealed that there is a significant difference in lignin content among the three pine species at 5 per cent level of variance. From Table 62 it can be found out that *Pinus caribaea* differ significantly from *Pinus patula* and *Pinus oocarpa.* But there is no significant difference between the lignin content of *Pinus patula* and *Pinus oocarpa.* The highest lignin content was found in *Pinus caribaea* (29.54 %) and lowest value in *Pinus oocarpa* (23.80 %). On the other hand, *Pinus patula* had 26.20 per cent lignin content (Fig. 63).

4.4 INTERRELATIONSHIP BETWEEN WOOD PROPERTIEES

4.4.1 *Pinus caribaea*

Table 63 gives correlation coefficient between different wood properties in *Pinus caribaea.* Tracheid diameter was found to be positively correlated with tracheid lumen diameter and negatively correlated with earlywood tracheid frequency. Tracheid wall thickness was negatively correlated with the tracheid lumen diameter. Earlywood tracheid frequency was found to be positively correlated with latewood tracheid frequency, whereas latewood tracheid frequency was positively correlated with latewood tracheid percentage and negatively correlated with latewood ray percentage. Specific gravity on oven dry basis was found to be correlated positively with air dry specific gravity.

4.4.2 *Pinus patula*

The correlation coefficient between wood properties in *Pinus patula* is presented in Table 64. From the table it can be seen that tracheid diameter is positively correlated with tracheid lumen diameter, whereas earlywood tracheid frequency was positively correlated with latewood tracheid frequency. Oven dry specific gravity was found to be positively correlated with air dry specific gravity.

Table 63. Correlation coefficient for the interrelationship between wood properties in *Pinus caribaea*

	TL	**TD**	**TWT**	**TLD**	**EWTF**	**LWTF**	**EWTP**	**EWRP**	**LWTP**	**LWRP**	**SGFW**	**SGAD**	**SGOD**
TL	1.000												
TD	-0.150												
TWT	-0.328	-0.352											
TLD	0.068	0.873**	-0.764**										
EWTF	-0.154	-0.493*	0.070	-0.377									
LWTF	-0.187	-0.396	-0.070	-0.237	0.719**								
EWTP	0.401	-0.128	-0.111	-0.030	0.040	-0.110							
EWTP	-0.399	0.134	0.110	0.035	-0.048	0.103	-1.000						
LWTP	0.108	-0.428	0.171	-0.384	0.456	0.592**	0.043	-0.054					
LWRP	-0.108	0.428	-0.171	0.384	-0.456	-0.592**	-0.043	0.054	-1.000				
SGFW	-0.105	-0.419	0.270	-0.430	0.399	0.219	-0.152	0.153	0.364	-0.364			
SGAD	-0.151	-0.025	0.250	-0.147	-0.158	-0.420	-0.105	0.100	-0.329	0.329	0.223		
SGOD	0.036	0.041	-0.036	0.047	-0.288	-0.465	-0.086	0.087	-0.435	0.435	0.163	0.882**	1.000

** significant at 1% level; * significant at 1% level; others are non significant

TL – Tracheid length; TD – Tracheid diameter; TWT – Tracheid wall thickness; TLD – Tracheid lumen diameter; EWTF – Earlywood tracheid frequency; LWTF – Latewood tracheid frequency; EWTP – Earlywood tracheid percentage; EWRP – Earlywood ray percentage; LWTP – Latewood tracheid percentage; LWRP – Latewood ray percentage; SGFW – Specific gravity (fresh weight); SGAD – Specific gravity (air dry); SGOD – Specific gravity (oven dry)

Table 64. Correlation coefficient for the interrelationship between wood properties in *Pinus patula*

	TL	TD	TWT	TLD	EWTF	LWTF	EWTP	EWRP	LWTP	LWRP	SGFW	SGAD	SGOD
TL	1.000												
TD	-0.289												
TWT	-0.305	0.292											
TLD	-0.108	0.825**	-0.299										
EWTF	-0.103	0.164	-0.189	0.275									
LWTF	0.336	-0.043	-0.357	0.168	0.602*								
EWTP	-0.072	-0.064	0.138	-0.145	0.242	0.276							
EWTP	0.075	0.062	-0.141	0.145	-0.233	-0.273	-1.000						
LWTP	0.403	0.146	-0.370	0.365	0.012	0.396	0.166	-0.163					
LWRP	-0.403	-0.146	0.370	-0.365	-0.012	-0.396	-0.166	0.163	-1.000				
SGFW	0.266	-0.346	-0.097	-0.287	0.075	0.079	-0.060	0.062	-0.188	0.188			
SGAD	0.179	0.150	0.331	-0.046	-0.273	0.138	0.094	-0.100	0.064	-0.064	-0.042		
SGOD	0.196	0.037	0.285	-0.131	-0.283	0.140	0.139	-0.146	-0.006	0.006	0.086	0.962**	1.000

** significant at 1% level; * significant at 1% level; others are non significant

TL – Tracheid length; TD – Tracheid diameter; TWT – Tracheid wall thickness; TLD – Tracheid lumen diameter; EWTF – Earlywood tracheid frequency; LWTF – Latewood tracheid frequency; EWTP – Earlywood tracheid percentage; EWRP – Earlywood ray percentage; LWTP – Latewood tracheid percentage; LWRP – Latewood ray percentage; SGFW – Specific gravity (fresh weight); SGAD – Specific gravity (air dry); SGOD – Specific gravity (oven dry)

4.4.3 *Pinus oocarpa*

Table 65 gives the correlation coefficient between different wood properties in *Pinus oocarpa.* From the Table 65, it can be seen that tracheid length was found to be positively correlated with tracheid lumen diameter and negatively correlated with air dry specific gravity. Tracheid lumen diameter was also found to be positively correlated with tracheid diameter and negatively correlated with tracheid wall thickness. Earlywood tracheid frequency showed a positive correlation with latewood tracheid frequency and earlywood tracheid percentage. Earlywood ray percentage showed a negative correlation with earlywood tracheid frequency and earlywood tracheid percentage. Air dry specific gravity was positively correlated with specific gravity on fresh weight basis, whereas oven dry specific gravity was found to be positively correlated with specific gravity on fresh weight basis and air dry specific gravity.

Table 65. Correlation coefficient for the interrelationship between wood properties in *Pinus oocarpa*

	TL	**TD**	**TWT**	**TLD**	**EWTF**	**LWTF**	**EWTP**	**EWRP**	**LWTP**	**LWRP**	**SGFW**	**SGAD**	**SGOD**
TL	1.000												
TD	0.570												
TWT	-0.149	-0.250											
TLD	0.518*	0.904**	-0.640**										
EWTF	-0.096	-0.266	0.079	-0.246									
LWTF	0.076	-0.041	-0.268	0.086	0.554**								
EWTP	0.209	0.103	0.288	-0.045	0.437*	0.103							
EWTP	-0.207	-0.060	-0.192	0.037	-0.444*	-0.099	-0.973**						
LWTP	0.200	-0.131	0.161	-0.175	0.299	0.133	0.187	-0.219					
LWRP	-0.200	0.131	-0.161	0.175	-0.299	-0.133	-0.187	0.219	-1.000				
SGFW	-0.133	0.053	0.108	-0.005	-0.263	0.002	-0.195	0.177	-0.146	0.146			
SGAD	-0.502*	-0.280	0.111	-0.271	-0.346	-0.213	-0.257	0.238	-0.147	0.147	0.516*		
SGOD	-0.432	-0.346	0.341	-0.425	-0.272	-0.210	-0.205	0.184	-0.098	0.098	0.510*	0.910**	1.000

** significant at 1% level; * significant at 1% level; others are non significant

TL – Tracheid length; TD – Tracheid diameter; TWT – Tracheid wall thickness; TLD – Tracheid lumen diameter; EWTF – Earlywood tracheid frequency; LWTF – Latewood tracheid frequency; EWTP – Earlywood tracheid percentage; EWRP – Earlywood ray percentage; LWTP – Latewood tracheid percentage; LWRP – Latewood ray percentage; SGFW – Specific gravity (fresh weight); SGAD – Specific gravity (air dry); SGOD – Specific gravity (oven dry)

4.5 REGRESSION ANALYSIS

4.5.1 Dependence of selected wood properties on radial positions

Linear regression model was used to show the dependence of selected wood properties on radial positions in the three pine species that were studied. The relationship was worked out by taking radial positions in the order of periphery, pith and middle. For this, complete set of data from all the plantations were used. The selected wood properties include tracheid length, tracheid diameter, tracheid wall thickness and air dry specific gravity. These results are presented in Tables 66 to 69.

Table 66 gives the regression equations that show the linear relationship between the dependent variable tracheid length and the independent variable radial positions. Regression analysis indicates a strong negative relationship between tracheid length and radial positions in *Pinus patula*, whereas *Pinus caribaea* and *Pinus oocarpa* showed no linear relationship.

Table 66. Regression equations showing the linear relationship between the dependent variable tracheid length and the independent variable radial positions

Species	Equation	Adjusted R^2 value
Pinus caribaea	y = -614.55x + 3464.07	0.210 (1.24^{ns})
Pinus patula	y = -906.98x + 5679.36	0.997 (24.62*)
Pinus oocarpa	y = -592.89x + 5204.27	0.797 (2.98^{ns})

* Significant at 5% level; ns – non significant; value in parentheses is t value of the regression coefficient

The regression equations showing the linear relationship between the dependent variable tracheid diameter and the independent variable radial positions in the three pine species are given in Table 67. From this, it can be seen there exist no significant linear relationship in the three species with regard to tracheid diameter and radial positions.

Table 67. Regression equations showing the linear relationship between the dependent variable tracheid diameter and the independent variable radial positions

Species	Equation	Adjusted R^2 value
Pinus caribaea	$y = -3.41x + 58.47$	0.880 (3.89^{ns})
Pinus patula	$y = -3.59x + 51.31$	0.940 (5.71^{ns})
Pinus oocarpa	$y = -3.04x + 56.51$	0.930 (5.43^{ns})

ns – non significant; value in parentheses is t value of the regression coefficient

Table 68 presents the regression equations showing the linear relationship between the dependent variable tracheid wall thickness and the independent variable radial positions. The linear relationship was found to be non significant in *Pinus caribaea,* whereas in both *Pinus patula* and *Pinus oocarpa* significant negative relationship existed between tracheid wall thickness and radial positions.

Table 68. Regression equations showing the linear relationship between the dependent variable tracheid wall thickness and the independent variable radial positions

Species	Equation	Adjusted R^2 value
Pinus caribaea	$y = -1.385x + 8.583$	0.974 (8.72^{ns})
Pinus patula	$y = -2.005x + 8.750$	0.992 (15.434*)
Pinus oocarpa	$y = -1.765x + 9.170$	0.998 (29.115*)

*Significant at 5% level; ns – non significant; value in parentheses is t value of the regression coefficient

The linear relationship between the dependent variable air dry specific gravity and the independent variable radial positions was represented by regression equation and presented in Table 69. There was no significant linear relationship between air dry specific gravity and radial positions in *Pinus caribaea*. However, in *Pinus patula* and *Pinus oocarpa* air dry specific gravity showed significant negative relationship with respect to radial positions.

Table 69. Regression equations showing the linear relationship between the dependent variable air dry specific gravity and the independent variable radial positions

Species	Equation	Adjusted R^2 value
Pinus caribaea	$y = -0.075x + 0.753$	0.600 (1.999^{ns})
Pinus patula	$y = -0.165x + 0.920$	0.995 (19.053*)
Pinus oocarpa	$y = -0.100x + 0.843$	0.993 (17.321*)

*Significant at 5% level; ns – non significant; value in parentheses is t value of the regression coefficient

4.4.2 Dependence among selected wood properties

Different regression model were used to show the interdependence of selected wood properties. The relationship was studied between air dry specific gravity and age; oven dry specific gravity and age; tracheid length and oven dry specific gravity; and between tracheid diameter and earlywood tracheid frequency. For this analysis, complete set of data from all the plantations were used and results are presented in Tables 70 to 73.

Table 70 gives the relationship between the dependent variable earlywood tracheid frequency and the independent variable tracheid diameter in the three pine species. Among the three pines species, only *Pinus caribaea* showed a significant relationship between the characters. Although there is an apparent negative relationship between the variables in this species, the predictions were found to be very weak, based on the low R^2 value.

Table 70. Regression equations showing the relationship between the dependent variable earlywood tracheid frequency and the independent variable tracheid diameter

Species	Equation	Adjusted R^2 value
Pinus caribaea	y = -8.88x + 899.35	0.243 (2.26*)
Pinus patula	No relationship	
Pinus oocarpa	No relationship	

* significant at 5 % level; value in parentheses is t value of the regression coefficient

Results of regression analysis indicating relationship between the dependent variable air dry specific gravity and the independent variable age in the three pine species are presented in Table 71, which shows that only *Pinus oocarpa* had significant relationship between the variables. The regression equation indicates that air dry specific gravity changes negatively with age. However, the predictions were found to be very weak, based on the low R^2 value.

Table 71. Regression equations showing the relationship between the dependent variable air dry specific gravity and the independent variable age

Species	Equation	Adjusted R^2 value
Pinus caribaea	No relationship	
Pinus patula	No relationship	
Pinus oocarpa	y = -0.0123x + 0.286	0.372 (3.354**)

** significant at 1 % level; value in parentheses is t value of the regression coefficient

Table 72 gives the regression equation showing the relationship between the dependent variable oven dry specific gravity and the independent variable age in the three pine species. Results show that, significant relationship exists between the variables in *Pinus oocarpa*, whereas others showed no significant relationship between the variables. However the negative relationship that is seen in *Pinus oocarpa* was found to be very weak based on the low R^2 value.

Table 72. Regression equations showing the relationship between the dependent variable oven dry specific gravity and the independent variable age

Species	**Equation**	**Adjusted R^2 value**
Pinus caribaea	No relationship	
Pinus patula	No relationship	
Pinus oocarpa	$y = -0.0125x + 0.235$	0.417 (3.687**)

** significant at 1 % level; value in parentheses is t value of the regression coefficient

Pinus oocarpa showed a negative relationship between tracheid length (dependent variable) and oven dry specific gravity (independent variable), whereas the other two species showed no significant relationship between the variables (Table 73). However the relationship was very weak due to low R^2 value.

Table 73. Regression equations showing the relationship between the dependent variable tracheid length and the independent variable oven dry specific gravity

Species	**Equation**	**Adjusted R^2 value**
Pinus caribaea	No relationship	
Pinus patula	No relationship	
Pinus oocarpa	$y = -2644.727x + 5724.962$	0.252 (2.53*)

* significant at 5 % level; value in parentheses is t value of the regression coefficient

Discussion

5. DISCUSSION

The variations in physical, anatomical and chemical properties of three tropical pine species viz., *Pinus caribaea* Morelet, *Pinus patula* Schl. et Cham. and *Pinus oocarpa* Schiede of different ages, with special reference to their suitability for pulping are discussed hereunder.

5.1 Specific gravity

The study revealed that specific gravity (fresh weight) had significant variation due to age and species influence, age and radial position influence. Furthermore, it has also shown significant difference between species across all ages and between radial positions within species across all ages. Compared to this, air dry specific gravity and oven dry specific gravity, both averaged across all ages, had difference between species and between radial positions.

Most commercial softwoods have oven-dry densities that lie between 400 and 600 kg/m^3 implying that the cell wall occupies on an average about one-third of the volume and that the other two-thirds are available for sap in the living tree or is occupied by air when cut and dried as lumber (Huang et al., 2003). Basic density varies greatly within and between species, being strongly influenced by geographic location, site fertility, age and genetics (Zobel and Talbert, 1984).

Of all the wood properties, specific gravity (density) is the most important descriptor of wood and also the most widely studied characteristic. It correlates with numerous morphological, mechanical, physiological, and ecological properties (Jerome et al., 2006). Furthermore, it is of importance in forest products manufacture because it has a major effect on both yield and quality of fibrous and solid wood products and because it can be changed by silvicultural manipulation (Zobel, 1961; van Buijtenen, 1962). It is a complex feature influenced by cell wall thickness, the proportion of the different kind of tissues, and the percentages of lignin, cellulose and extractives (Valente et al., 1992). This expresses how much wood substance is present per unit volume and has a significant effect on the quality and yield of pulp and paper products and on strength and utility of solid wood products. It appears to influence machinability, conversion, strength, paper yield and many other properties (Wimmer et al., 2002).

There are several reports stating the species difference in pines regarding specific gravity. De Villiers (1974) studied timber properties of tropical pines grown in South Africa and reported that density is found to have varying values between species. Similar to this, Robertson (1991) studied the pulping characteristics of *Pinus tecunumanii, Pinus patula* and *Pinus taeda* grown in South Africa. He found significant variation among species with regard to weighted density, whereas Malan (1994) studied the wood properties among four pine species and found significant differences between species for early wood density. Clarke et al. (2003) reported species difference in wood density among *Pinus patula, Pinus elliottii, Pinus taeda, Pinus kesiya* and *Pinus maximinoi.* The results obtained in the present study also showed difference in wood density among the three pine species studied.

Several authors such as Bryce (1967), Lamb (1973), and Plumptre (1984) report that the density of *Pinus caribaea* is quite variable. Plumptre (1984), for example, reports a coefficient of variation of 13.2 per cent for material grown in Fiji. The values obtained for oven dry specific gravity (density) of *Pinus caribaea* (average of 0.55), for all the ages put together in this investigation is slightly greater in comparison to those obtained by several other investigators (Orwa et al., 2009; Goche-Telles et al., 2003; Stanger, 2002). Compared to the observations made by Correa calderon (1988) and Wright and Malan (1991), in the present study *Pinus patula* had lower values for fresh weight specific gravity and higher values for oven dry specific gravity. On the other hand, *Pinus oocarpa* had a higher mean wood density compared to those reported by Mendes et al. (1999) and Moura et al. (1991). These differences in wood specific gravity values with that of previous workers might be due to the influence of age, growth rate or provenance variation of the species studied (Savva et al., 2010; Watt et al., 2010; Fries and Ericsson, 2006; Correa calderon, 1988).

The variation patterns in wood specific gravity between age levels within species was found to be non consistent. Tree-to-tree genetic and environmental effects had greater influence in deciding the wood specific gravity in tree species (Barnes et al., 1999; Jayawickrama, 2001; Hodge and Purnell, 1993; Gwaze et al., 2000). In the case of fresh weight specific gravity, age and species influence had a significant influence which resulted in such a pattern of variation, whereas in the other two cases, age and species influence was found to be non significant. So, the difference in specific gravity might be due to genetic or environmental influence or the number of trees sampled.

Generally, basic density increased with age especially between the transition periods of 15 years to mature period at 20 years due to increasing age as more mature wood is formed. However, the higher rate of variability observed in the lower age series might be due to the juvenile nature of the wood (Oluwadare, 2007; Panshin and de Zeeuw, 1980). In their review of wood variation, Zobel and van Buijtenen (1989) concluded that there is a very strong positive correlation between age and wood density for the first 20 years but that the correlation is not nearly so pronounced from 20 years onwards.

The pattern of variation in specific gravity (fresh weight) was found to have general trend of gradual increase from pith to periphery, whereas air dry and oven dry specific gravity did not show any consistent pattern of variations. In few cases it showed increase from pith to periphery, whereas in others it decreased at the middle position and then increased at periphery position.

It is thought that radial increases in wood density result from a shift in allocation from low density wood and rapid height growth early on in tree development to denser wood and structural reinforcement as trees increase in size, age and height and are exposed to increasing wind speeds (Wiemann and Williamson, 1989b). In a previous study of the effects of tree size and age on radial gradients in wood density, de Castro et al. (1993) presented evidence that tree age was likely to be the driver of radial increases in wood density for a single cohort of *Joannesia princeps* grown in a Brazilian plantation. Similar results were observed by Onilude and Oluwadare (2000) in *Pinus caribaea* where mean basic density varied from 402 kg/m^3 at the pith area to 603 kg/m^3 towards the bark. Borja et al. (2001) also observed an increase in proportion of latewood and basic density with distance from the pith, whereas Muneri and Balodis (1998) reported a 50 per cent radial increase in wood density in *Pinus patula*. The above pattern of variation was similar to those obtained in this investigation also.

It is apparent from other studies (Dinwoodie, 1966; Watson and Hodder, 1954; Watson et al., 1952) that wood density is a factor in the ultimate performance of fiber as a raw material for pulp. General trend in wood property-pulp and paper property research emphasize that increase in wood specific gravity are accompanied by increase in tear index, bulk, air permanence, freeness, bending stiffness, light scattering and opacity, while it reduces tensile index, stretch, bursting strength, breaking length, Tensile Energy Absorption (T.E.A) and fold endurance (du Plooy, 1980; Malan et al., 1994; Wimmer et al., 2002). On the other hand, handsheets made from the high specific gravity trees results in open textured, bulky sheets of lower apparent density (Einspahr et al., 1969). Other studies showed that an increase in density decreases burst and tensile strength while increasing tear strength and pulp yield (Kleppe, 1970; Farrington, 1980; Kibblewhite, 1984; Duffy and Kibblewhite, 1989). Nevertheless, wood that is high in density in excess of 600 kg/m^3 and above may not be suitable for paper making (Chittenden and palmer, 1990). Ikemori et al.

(1986) suggested that density which is in the range of 480-570 kg/m^3 is ideal for paper and pulp. In the present study, *Pinus oocarpa* was found to have higher specific gravity followed by *Pinus patula* and *Pinus caribaea.* It was also found out that among three pine species studied, only *Pinus caribaea* had specific gravity within the range suggested by Chittenden and Palmer (1990). So, selection of species for pulping should be taken up by considering the above aspects.

5.2 Tracheid morphology

Tracheid morphological parameters such as diameter and lumen diameter were found to have significant variation between species, whereas tracheid length and fiber wall thickness did not vary with respect to species. The results of this study also revealed that, there is no significant influence of species and age on tracheid morphological parameters.

Cell size and relating dimensions of tracheids have a major influence on the quality of paper and pulp products as well as solid wood products (Clark, 1962). In conformity with the results obtained in the present study, Wright and Sluis (1992) reported slight variation between *Pinus caribaea* and *Pinus oocarpa* for tracheid characters viz., tracheid diameter, lumen width, and wall thickness. Muneri and Balodis (1998) studied the tracheid length variation in *Pinus patula* species at two age levels (14 years and 25 years) and reported an increase in the values with age. The average tracheid length observed in that study was in the range of 3.07 to 3.87 mm. This was in conformity with the results obtained in the present study in *Pinus patula*. Similar range of values was reported by Ishengoma et al. (1990), who studied tracheid length variation in *Pinus patula* that were 29 years old. Nigro (2008) in his study reported that *Pinus patula* had tracheids in the range of 2.0 to 4.9 mm long and 36 to 57 µm wide, with a cell wall thickness of 4.0 to 5.5 µm. The present study also showed similar results.

Oluwadare (2007) reported a significant increase in tracheid length and cell wall thickness with age in *Pinus caribaea*. In that report he observed greater variation in the tracheid characters in the early years viz. 5 to 7 years. But the present study had no such variation in tracheid morphology with age. Generally, tracheid length increased with tree age due to aging of cambium (Baskent et al., 2005). The benefit of this is that better paper with higher paper strength will be produced provided there is no concomitant increase in other cell parameters especially cell wall thickness. But the present study shows no such variation with age which is indicating that the cambium came to maturation stage in earlier years itself. So wood is having more percentage of mature wood compared to juvenile wood portion and this might have nullified the effect of variation in properties with age. The transition age for transformation from juvenile to mature wood is decided by genetic makeup of the species. But this factor is greatly influenced by environment also. So under the present climatic conditions prevailing in the site, such transition might have happened in the earlier stage itself.

The species variation in tracheid morphology was also reported by Via et al. (2004). Existence of such variation between species for the tracheid morphological traits indicates good opportunities for exploitation of these species and superior trees among them for further tree improvement works and for specific end uses. This is because of the fact that tracheid properties of wood are of great importance in pulp and papermaking. The increase in fiber length results in increased pulp yield, tear index, bending stiffness, freeness burst strength and permanence, whereas reduction in fiber length does reduce the physical strength properties with reduced soda demand (du Plooy, 1980; Labosky and Ifju, 1981; Malan et al., 1994; Hosseiny and Anderson, 1999; Wimmer et al., 2002). The loss of fiber strength has little effect on the sheet structural and optical properties. In conformity with this eucalyptus (*Eucalyptus globulus*) had tensile, tear, bending, freeness, and pulp yield that were positively correlated to fiber length (O'Neill, 1999; Wimmer et al., 2002). But in a general sense, both short and long fibres are required to furnish good grade paper where as to certain extent the quality of paper is decided by the quality of its fibres.

The radial changes in wood properties other than specific gravity could be described as perplexing. Nearly every possible pattern of variation may occur. Tracheid morphology did not show similar pattern radially in all the four ages in which the three pine species were studied. However, it is important that the pattern for each species be determined for the site on which the trees are grown (Zobel and van Buijeten, 1989). The significant variation found within the trees and among the species in this study is also suggestive of the juvenile nature of the trees and the conditions under which they are grown.

From pith to bark, fiber length was shown to increase for pino rojo (*Pinus sylvestris*), radiata pine (*Pinus radiata*), loblolly pine (*Pinus taeda*), eastern cottonwood (*Populus deltoides*), and Douglas-fir (*Pseudotsuga menziesii*) (Zobel et al., 1960; Boyce and Kaeiser, 1961; Dadswell et al., 1961; Koch, 1972; Piedra and Zobel, 1986; Goyal et al., 1999). Similar results were reported by Wimmer et al. (2002) in which he observed an increase in tracheid length, tracheid diameter and wall thickness from pith to bark. The results of the present study also shows similar increasing trend in tracheid characters from pith to periphery.

Morphological variations from pith to bark are, quite often, more pronounced than vertically for many species (Evans et al., 1997; Koubaa et al., 1998; Raymond et al., 1998). For scots pine (*Pinus sylvestris*), the COV (Coefficient of variation) for tracheid length was 7 per cent at both ring 4 and 24 (Hannrup et al. 2001).

Tracheid length, diameter, lumen diameter and wall thickness were found to influence bulk, burst, tear, fold and tensile strength of the paper. For example Horn (1974) reported that the papers made from tracheids of thick cell walls are having lower bursting and tensile strength, whereas lower cell wall thickness of tracheids results in paper having higher double folding strengths (Tutus et al., 2010). However, it is not possible to fully characterize the performance of a pulp by a single morphological factor. Coarse tracheids are known to have same effect on paper as short tracheids. Tracheid characteristics such as tracheid diameter, lumen diameter and wall thickness has profound influence on specific gravity. Each character has been shown to have its own inheritance pattern as they are genetically independent (Matziris and Zobel, 1973; Nicholls et al., 1964; Dadswell et al., 1961; Ivkovich et al., 2002). Hence care has to be exercised in screening the species for tree improvement works based on these tracheid morphological values alone.

5.3 Ratios and factors

Considering the importance of pines as raw material for paper and pulp, the different types of ratios like Runkel ratio, slenderness ratio (felting rate or peteri coefficient), coefficient of flexibility, coefficient of rigidity and shape factor were determined from the basic data on tracheid morphology. All the five factors showed significant difference between the three radial positions, whereas no difference was observed due to age.. On the other hand, species difference was observed in the case of slenderness ratio only. Jahan-Latibari et al. (2004) reported similar radial variation in the derived ratios. These variations in the ratios are the result of corresponding radial variation in tracheid morphology (Fig. 14, Fig.17, Fig. 20 and Fig. 23).

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). In studies utilising *Pinus radiata* and *Pinnus elliottii* for Kraft pulp production, it was found that the Runkel ratio was the best fibre dimension ratio, and accounted for 80 to 85 per cent (Barefoot et al., 1964; Kibblewhite, 1982) of the variation in the hand sheet tear. So far as Runkel ratio is considered, the approximate limits appears to be from 0.25 to 1.5 (Singh et al., 1991) for species, whereas

Dadswell and Wardrop (1959) suggested less than 1 which can produce pulp of reasonable quality. Similar to this, the guidelines by Okereke (1962) and Rydholm (1965) show that for good paper characteristics, the Runkel ratio will be ≤ 1, because paper strength tends to improve with decreasing Runkel ratio. The results obtained in the present investigation suggest the suitability of the three pine species in all the age groups which follows the suggested criteria. All the three pine species studied showed an increase in Runkel ratio from pith to periphery (Fig. 26). This might be due to the increase in tracheid wall thickness radially i.e. from pith to periphery (Fig. 20), while tracheid lumen diameter did not have large difference among radial values (Fig. 23).

Shape factor was also found to have an increasing pattern radially i.e. from pith to periphery (Fig. 29). 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. The results of the study suggest the suitability of *Pinus caribaea* as a potential one over the other species for pulping, since it has the lowest value for shape factor among the three species studied (Table 26).

Similarly, slenderness ratio also showed significant difference between the three radial positions in all the three species (Fig. 32). This is due to corresponding changes in tracheid length and diameter with radial position (Fig. 14 and Fig. 17). 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, more easy to drain the water in the wet end of the paper-machine (Foelkel, 1998). It is stated that if felting coefficient or 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). Among the three pine species *Pinus patula* and *Pinus oocarpa* had higher slenderness values compared to *Pinus oocarpa* (Table 29).

Elasticity coefficient is also referred as Istas coefficient or flexibility coefficient or coefficient of suppleness and it is related with individual elasticity of fibers. According to elasticity rate there are four groups of fibers (Bektas et al., 1999).

- Highly elastic fibers having elasticity coefficient greater than 75
- Elastic fibers having elasticity ratio 50 to 75
- Rigidity fibers having elasticity ratio 30 to 50
- Highly rigid fibers having elasticity less than 30

In studies on softwoods, elasticity coefficient was found as 60.02 for *Pinus sylvestris* (Akkayan, 1983), 62.71 for *Pinus brutia* (Bektas et al., 1999), 66.92 for *Picea orientalis* (Bostanci, 1976) and 63.32 for *Pinus pinaster* (Bektas et al., 1999). Based on this information, it appears that the three pine species in the present study can be included in the highly elastic fiber category. *Pinus caribaea* is having highest elasticity coefficient compared to the other two species. The three radial positions differ significantly from each other and it shows a decreasing pattern from pith to periphery in all the three pine species (Fig. 35). This is because of the fact that tracheid diameter increases from pith to periphery, while lumen diameter did not show much difference along the radial positions (Fig. 23 and Fig. 17).

Peteri (1952), Okereke (1962) and Rydholm (1965) demonstrated that a higher coefficient of suppleness (preferably > 60) is necessary for fibres used in paper-making. This is because, paper strength tends to improve with increasing elasticity coefficient. Fibres with high elasticity coefficient are flexible, collapse readily and produce good surface contact and fibre-to-fibre bonding. They yield low bulk paper with excellent physical characteristics (burst, tensile and fold). Considering this criteria, all the three species were found to have elasticity coefficient greater than 60 in all the age levels.

Rigidity coefficient is a measure of physical resistance properties of paper. Higher values for this coefficient affect tensile, tear, burst and double fold resistance of paper negatively (Hus et al., 1975). Rigidity coefficient regarding softwoods were found as 19.97 for *Pinus sylvestris* (Akkayan, 1983), 20.00 for *Pinus brutia* (Bektas et al., 1999), 16.24 for *Picea orientalis* (Bostanci, 1976) and 17.82 for *Pinus pinaster* (Bektas et al., 1999). In the present study, *Pinus caribaea* had lowest value for rigidity coefficient compared to the other two species. So this species will produce paper having better quality compared to the other two. Present study also showed an increasing pattern in values from pith to periphery. This is due to the corresponding relative increase in tracheid wall thickness and tracheid diameter from pith to periphery.

5.4 Ray morphology

Ray height and ray width were studied along radial positions viz. pith, middle and periphery. The study revealed that age and species was found to have significant influence in ray morphology (Fig. 39B and Fig. 42B). Radial positions were also found to differ significantly with regard to ray morphology in the three pine species studied (Table 38 to Table 43).

Ayaz and Nasir (1992) reported ray height as 8192 mm for *Pinus eldarica*, 6169 mm for *Pinus geradiana*, 7310 mm for *Pinus roxburghii* and 6162 mm for *Pinus wallichiana*. In contrast to these results, the three pine species in the present study had lower values for ray height. Generally, ray height changes periodically as tree grows. This increase in ray height with tree age is as a result of transverse division of ray cell initials, fusiform initials of adjacent rays, or addition of segments from fusiform initials. Environment has a greater influence in deciding the size of ray height. This is because of the fact that an environmental stress reduce rate of cambial growth there by height of ray height may be reduced (Larson, 1994).

Literature results on patterns of pith to bark increases in ray size was reported by several researchers (Bannan, 1937, 1954; Gregory and Romberger, 1975; Lev-Yadun, 1998; Mohammed Mohiuddin Denne, 2000). For example, radial variation in ray height was reported by Lev-Yadun (1998). In this study, he observed a gradual increase of ray height radially i.e. from pith to periphery in *Pinus halepensis* and *Pinus pinea*. The results of the present study showed similar radial pattern of variation in ray height in all the three pine species studied.

In general, ray width was also found to show periodic changes as the tree grows. This increase happens by anticlinal division of initial cells within rays or by merging of rays (Larson, 1994). The width increases with increase in tree age in very young trees and stabilize there after. Iqbal and Ghouse (1987) also reported similar changes in ray width with tree age. Seasonality was also found to influence ray width, increasing in the quiescent season and decreasing during the season of active growth when ray split. The difference in pattern of variation within each species with age might be due to these environmental influences. This also accounts for the variation in genetic make up of species belonging to different age levels. A study by Ayaz and Nasir (1992) reported ray height as 223 mm for *Pinus eldarica*, 117 mm for *Pinus geradiana*, 228 mm for *Pinus roxburghii* and 114 mm for *Pinus wallichiana*. In the three pine species included in the present study ray width was within the same range (Table 41).

5.5 Tissue frequency

Tissue frequency was studied radially in both earlywood and latewood part of the ring. The study revealed significant difference in tracheid frequency due to species and age influence in both earlywood and latewood, whereas influence due to radial position and age was found to be significant only in the case of latewood.

In general, within a ring, early wood tracheid will be having large tracheid length compared to latewood portion. There are several reports stating similar variation pattern along the radial direction (Wang Fang et al., 2009; Rathgeber et al., 2006; Gindl and Wimmer, 2000). The increasing trend in tracheid diameter were considered to be inherent to tree growth, presumably associated with cambial ageing, since they occurred in all trees on all sites (Mitchell and Denne, 1997). On the other hand, this increase in tracheid diameter will correspondingly results in decrease in tracheid frequency. It has been reported that latewood formation is influenced by climate especially related to availability of water (Berges et al., 2008). All these could explain pattern of variation in tracheid frequency that is observed in the present study (Fig. 47 and Fig. 50).

5.6 Tissue proportions

Tissue proportions viz., tracheid percentage and ray percentage were studied both in earlywood and latewood at pith, middle and periphery position. The results showed significant difference regarding tissue proportion only in the latewood portion. In this, both ray and tracheid percentage had significant difference radially. Age and species influence also showed significant difference in tissue proportion in the latewood.

Tissue proportion is greatly influenced by environmental condition, especially rate of growth which decides upon the proportion of juvenile wood and mature wood in the tree which in turn influence tissue proportion. In a study by

Ma Shun Xing et al. (2006), significant difference in tissue proportion was observed among the clones of Japanese Larch. This indicates the influence of environment in deciding tissue proportion. They also reported a rapid decline in ray proportion in the beginning while declined or rose later on from pith to outward. This was in conformity with the results obtained in the present study. On the other hand, tracheid percentage showed a pattern opposite to that showed by ray percentage from pith to periphery. This might be due to the result of spatial adjustment required in relation to other cell types and their dimensions. All together, the information generated on tissue proportion species shed light on variation patterns but also their possible role in utilization for paper and pulp.

5.7 Chemical properties

The study revealed significant difference in cellulose content among the three pine species. *Pinus oocarpa* (47.555) had higher cellulose content followed by *Pinus patula* (40.32%) and *Pinus caribaea* (33.54%). These differences in cellulose content among the species might be due to variation in the oven dry specific gravity among the species (Table 8). Both these characters had similar pattern of variation i.e. in case of oven dry specific gravity, the values were found to be highest in *Pinus oocarpa* (0.671) followed by *Pinus patula* (0.555) and *Pinus caribaea* (0.499). Sreejith (2009) reported similar variation among these three species. In this study, *Pinus oocarpa* (46.75 %) had maximum cellulose content followed by *Pinus patula* (41.33 %) and *Pinus caribaea* (30.15 %).

Heldebrandt (1960) emphasizes the importance of chemical composition and its influence on wood mechanical properties. Scurfield et al. (1974) reported that variability resulting from differences in extractives or chemical composition influences wood density and cause great differences in utility of wood. Silva et al. (2004) estimated chemical composition of *Pinus caribaea* wood showing average cellulose content of 45.93 percent. Similar results were observed by Moura and Brito

(2001) in their study on basic density, chemical composition and tracheid characteristics of *Pinus caribaea.* They reported that, in *Pinus caribaea* the cellulose content varied from 47.13 ± 0.69 per cent to 49.62 ± 0.83 per cent.

Barnes et al. (1999) determined the effect of rotation age and site altitude on the quality of unbleached kraft pulp made from *Pinus elliottii* and *Pinus patula.* In this study, alpha-cellulose content showed a mean value of 42.18 per cent. The chemical composition of *Pinus oocarpa* wood cultivated in the Brazilian cerrado was estimated by Morais et al. (2005). The obtained results were alpha-cellulose (59.05%) and hemicelluloses A and B (21.22%). Results from the present study on cellulose content showed lower values as compared to the values obtained from previous research works. Though chemical properties like cellulose content are directly related to the genetic features, sometimes it may be influenced by environmental factors also (Heldebrandt, 1960).

Lignin content showed significant difference among the three pine species studied. Among the three pine species studied, *Pinus caribaea* (29.54%) was found to have maximum lignin content. This was followed by *Pinus patula* (26.20%) and *Pinus oocarpa* (23.80%). For pulping, wood with lower lignin content is preferred as this greatly reduces the coast of chemicals used for its removal.

Andrew et al. (1997) in a study found that *Pinus patula* (28.3%-27.8%) has a lower lignin and extractive content than *Pinus elliottii* (28.2%-30.4%), and this chemical difference resulted in the superior pulp yield of *Pinus patula.* Likewise, Barnes et al. (1999) reported similar range of values for lignin content in *Pinus patula* and *Pinus elliottii*, whereas in another study Kibblewhite and Shelbourne (2003) found that the lignin content ranged from 26.6 per cent to 31.7 per cent in 13 years old *Pinus radiata.* The chemical composition of *Pinus oocarpa* wood cultivated in the Brazilian cerrado was estimated by Morais et al. (2005). Here, *Pinus oocarpa* (25.18%) had low lignin content compared to this study. Lower lignin content is always a desirable character since it greatly reduces the cost of chemicals used for its removal. The present study had similar range of values for lignin content in the pine species studied.

The wood chemical properties evaluated in this study are important in pulp and paper production. From the results it is clear that *Pinus oocarpa* is superior to the other two species in terms of suitability for pulping owing to the higher cellulose content and lower lignin content. The cellulose content relates to the amount of pulp that can be obtained from wood. The higher the cellulose content in a tree, the more pulp the tree will produce (Sykes et al., 2003). Increasing the amount of cellulose content in wood will reduce pulping costs and increase the efficiency of the pulp and paper mill. On the other hand, increased amount of lignin content in wood will increase pulping cost by necessitating the chemical breakdown of lignin, which is an expensive process. So reducing the lignin content in wood could save processing costs for the pulping industry (Sykes et al., 2003).

But as cited earlier, the chemical properties are greatly influenced by environmental conditions (presumably either temperature and/or day length). Further work is needed to determine the exact nature of the environmental control. This will help in popularizing the pine plantation in areas where environment favours greater cellulose production and lesser lignin production.

5.8 Inter relationship among wood properties

Interrelationships between all the wood properties are shown in table 63 to 65. Most of the wood properties did not show any significant relationship between them. This might be due to the low sample size and variations due to age and species influence. However, in the case of *Pinus caribaea,* tracheid diameter was found to be negatively correlated with earlywood tracheid frequency. So, under the present environmental and climatic condition, earlywood tracheid frequency could be predicted by knowing tracheid diameter, the latter being more easy to measure compared to the former. Similarly air dry specific gravity was found to be negatively correlated with fiber length in the case of *Pinus oocarpa.* This aspect offers good potential in breeding programme, as it help in deciding to what extent the specific gravity (air dry) need to be improved without adversely influencing tracheid length. All these inter relationships will also help in deciding to which species need to be selected for pulping and paper making, as each property has its own implications in the final product made out of it.

5.9 Regression analysis

There was difficulty in developing prediction equations relating to selected wood properties and radial positions. Low sample size, and the influence of age and species interaction would have contributed to this. However, both *Pinus patula* and *Pinus oocarpa* showed radial relationship with tracheid wall thickness and air dry specific gravity. Among the three species only *Pinus patula* showed radial relationship with tracheid length. The importance of this linear relationship between the wood properties and radial position will help in determining radial variation of the concerned wood property.

5.10 Conclusion

Relationships in wood and fibres can be complex - a mixture of direct and indirect links which determine the pulping properties (Wimmer et al., 2002; Watson and Dadswell 1961, 1962, 1964a, 1964b). The prediction of pulp/paper quality from wood properties used to be limited by our ability to efficiently measure the appropriate fibre properties.

There is considerable evidence in the literature which suggests that specific gravity and associated fiber morphology appears to have considerable influence on pulp and paper properties. The results of the present study showing these properties and their acceptable range are shown in Table 74. These results account for the variation due to species and age influence. It can be concluded that under the prevailing eco-climatic conditions in the high ranges of Idukki district of Kerala, *Pinus caribaea* was found to perform better with superior wood properties that were within the acceptable range for pulping and papermaking (Table 74). *Pinus patula* and *Pinus oocarpa* were also found to be promising species for pulping and papermaking with better derived fiber ratios. However, *Pinus oocarpa* had larger specific gravity value than that is recommended for pulping and paper making. In contrast to this, among the three pine species studied, *Pinus oocarpa* had higher cellulose and lower lignin content, which is another preferred criteria for selection of a species for pulping and paper making. So a subjective judgment in selection is to be made by taking all these criteria as a whole so that the desired objective can be accomplished. More elaborate study is needed in the point of view of chemical characteristics and its variation with age in order to decide up on the maximum profitable age of harvest.

Each characteristic has its own influence on pulping and properties of final paper manufactured out of it. Therefore, an effective criteria of selection should be developed by giving weightage to these properties based on the kind of pulp required and the final product that need to be made out of it. What needs to be determined is the relationship, if any, between wood and tracheid properties of these species and the products which can be manufactured from this renewable resource. For this, more elaborate study is needed for which the results of this study could be utilized as a base line data. The information could be further utilized for future tree improvement aspects of these species with reference to wood quality and to bring out their potential utility for future afforestation programmes and timber utility.

Table 74. Mean values of selected wood properties of pine species averaged over all ages compared with acceptable range of values for pulping and papermaking

Wood properties	**Species**			**Acceptable range**
	Pinus caribaea	***Pinus patula***	***Pinus oocarpa***	
Specific gravity (oven dry)	0.550	0.575	0.630	≤ 0.600 (Chittenden and palmer, 1990)
Tracheid length (μm)	4076.48	3855.49	4003.63	longer the better (Wimmer et al., 2002)
Runkel ratio	0.27	0.33	0.37	≤ 1 (Okereke, 1962)
Shape factor	0.22	0.25	0.26	lower the better (Page and Seth, 1980)
Slenderness ratio	77.24	88.79	80.96	> 70 (Young, 1981; Bektas et al., 1999)
Coefficient of flexibility	80.28	77.73	77.26	> 60 (Peteri, 1952; Okereke, 1962; Rydholm, 1965)
Coefficient of rigidity	19.72	22.27	22.74	lower the better (Hus et al., 1975)

Summary

6. SUMMARY

Three tropical pine species viz. *Pinus caribaea* Morelet, *Pinus patula* Schl. et Cham. and *Pinus oocarpa* Schiede, grown in research trials of the Kerala Forest Department in the high ranges of Idukki District, Kerala were evaluated for their wood quality, for pulp and paper making. The study was carried out at the College of Forestry, Kerala Agricultural University, Vellanikkara, Kerala during 2008-2010. The salient findings of the study are as follows:

- Significant difference in specific gravity was observed among species and radial positions in all the three conditions viz., fresh, air dry and oven dry weight basis. Age and species interaction, and age and radial positions interaction was, however, found to differ only in the case of fresh weight specific gravity. It was also found that both *Pinus caribaea* and *Pinus patula* had mean specific gravity (oven dry) within the range suggested for pulping and paper making, whereas *Pinus oocarpa* is having a value above the desired range.

- Tracheid length showed significant difference between radial positions in each species. Among the three pine species, *Pinus caribaea* had the highest tracheid length followed by *Pinus oocarpa* and *Pinus patula.*

- Tracheid diameter was found to have difference between species and radial positions within the species. In this study, *Pinus caribaea* had highest value for tracheid diameter followed by *Pinus oocarpa* and *Pinus patula.*

- Significant difference in tracheid wall thickness was found between radial positions within the species. Among the three pine species, *Pinus oocarpa* had the highest tracheid wall thickness followed by *Pinus caribaea* and *Pinus patula.*

- The variation in tracheid lumen diameter was found to be significant between species. *Pinus caribaea* had highest lumen diameter followed by *Pinus oocarpa* and *Pinus patula.*

- Radial variation was found to be significant within species with respect to Runkel ratio. All the three species had Runkel ratio within the acceptable range for pulping and paper making. Among the three species, *Pinus oocarpa* had highest Runkel ratio followed by *Pinus patula* and *Pinus caribaea.*

- Shape factor was found to have significant radial difference within the species. All the three species had lower values indicating their suitability for pulping and papermaking. Among them, *Pinus caribaea* had lowest value followed by *Pinus patula* and *Pinus oocarpa.*

- Significant difference was observed between species and radial positions within the species with regard to slenderness ratio. Average mean slenderness values of the three species suggests their suitability for pulping and paper making. Among them, *Pinus patula* had the highest slenderness value, followed by *Pinus oocarpa* and *Pinus caribaea.*

- Coefficient of flexibility had significant radial differences within the species. The mean coefficient of flexibility of the three pine species averaged across all ages was found to be within the accepted range for pulping and paper making. Among the three species, *Pinus caribaea* had the highest value followed by *Pinus patula* and *Pinus oocarpa.*

- Radial difference within the species was found to be significant with regard to coefficient of rigidity. All the three species were found to have lower values for coefficient of rigidity indicating their suitability for pulp and paper making. *Pinus caribaea* had the lowest value followed by *Pinus patula* and *Pinus oocarpa.*

- Radially, ray height differed significantly within the species. Among the three pine species studied, *Pinus caribaea* had the highest ray height followed by *Pinus oocarpa* and *Pinus patula.*

- Age and species interaction differed significantly with respect to ray width. Radial variation was also found to have significant difference within the species. In this, *Pinus caribaea* had highest ray width followed by *Pinus oocarpa* and *Pinus patula.*

- Age and species interaction, and age and position within the species interaction were found to be significant with respect to earlywood tracheid frequency. Among the three pine species studied, *Pinus patula* had highest value for earlywood tracheid frequency followed by *Pinus oocarpa* and *Pinus caribaea.*

- Significant variation was observed in latewood tracheid frequency with respect to age and species interaction, and age and position within the species interaction. For this property, *Pinus patula* had the highest value followed by *Pinus oocarpa* and *Pinus caribaea.*

- Earlywood tracheid percentage was observed to have higher value in *Pinus caribaea* followed by *Pinus oocarpa* and *Pinus patula.*

- *Pinus patula* had higher ray percentage in earlywood followed by *Pinus oocarpa* and *Pinus caribaea.*

- Significant difference was observed in latewood tracheid percentage with regard to age and species interaction and radial positions within the species. *Pinus patula* had higher latewood tracheid percentage compared to *Pinus caribaea* and *Pinus oocarpa*, whereas the latter two had similar values.

- Latewood ray percentage had significant variation with respect to age and species interaction and between radial positions within the species. *Pinus patula* had higher latewood ray percentage compared to *Pinus caribaea* and *Pinus oocarpa,* whereas the latter two had similar values.

- Cellulose and lignin content were found to differ between species that belonged to 1975 plantation (35 years old). Cellulose content was found to be highest in *Pinus oocarpa* followed by *Pinus patula* and *Pinus caribaea.* On the other hand, *Pinus caribaea* had a higher value for lignin content followed by *Pinus patula* and *Pinus oocarpa.* This suggests suitability of *Pinus oocarpa* for pulping and paper making.

- In *Pinus caribaea,* pooled data for all the positions averaged across all ages showed significant positive correlation between characters such as tracheid diameter and tracheid lumen diameter; earlywood tracheid frequency and latewood tracheid frequency; latewood tracheid frequency and latewood tracheid percentage; and air dry specific gravity and oven dry specific gravity. Negative correlation was observed between characters such as tracheid diameter and earlywood tracheid frequency; tracheid diameter and latewood tracheid frequency; tracheid wall thickness and tracheid lumen diameter; and latewood tracheid frequency and latewood ray percentage.

- Pooled data for all the positions averaged across all ages of *Pinus patula* showed significant positive correlation between characters such as tracheid diameter and tracheid lumen diameter; earlywood tracheid frequency and latewood tracheid frequency; and air dry specific gravity and oven dry specific gravity.

- In *Pinus oocarpa,* pooled data for all the positions averaged across all ages showed significant positive correlation in characters such as tracheid length and tracheid lumen diameter; tracheid diameter and tracheid lumen diameter; earlywood tracheid frequency and latewood tracheid frequency; earlywood tracheid frequency and earlywood tracheid percentage; fresh weight specific gravity and air dry specific gravity; fresh weight specific gravity and oven dry specific gravity; and air dry specific gravity and oven dry specific gravity, whereas negative correlation was observed between characters such as air dry specific gravity and tracheid length; tracheid wall thickness and tracheid lumen diameter; earlywood tracheid frequency and earlywood ray percentage; and earlywood tracheid percentage and earlywood ray percentage.

- Regression equation was worked out showing significant linear relationship between variables such as tracheid length and radial positions in *Pinus patula* and *Pinus oocarpa*; wall thickness and radial positions in *Pinus patula* and *Pinus oocarpa*; air dry specific gravity and radial positions in *Pinus patula* and *Pinus oocarpa*; earlywood tracheid frequency and tracheid diameter in *Pinus caribaea*; air dry specific gravity and age in *Pinus oocarpa*; oven dry specific gravity and age in *Pinus oocarpa*; and tracheid length and oven dry specific gravity in *Pinus oocarpa.*

Significant differences within species and between species for the specific gravity, tracheid properties and chemical properties found in this investigation would suggest that these properties can possibly be altered either through silvicultural techniques, genetic manipulation or their combination. What needs to be determined is the relationship, if any, between wood and tracheid properties of these species and the products which can be manufactured from this renewable resource. In this regard, more extensive study is needed for which the results of this study could be used as a base line data for future tree improvement and breeding programme.

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Appendices

APPENDIX

I. Results of ANOVA for comparing Specific gravity (fresh)

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	0.12	0.04	6.07**
Species	2	0.13	0.06	9.46**
Age x species	6	0.20	0.03	4.97**
Error 1	24	0.16	0.01	
Position within species	6	0.89	0.15	20.65**
Age x Position within species	18	0.30	0.02	2.32*
Error	48	0.34	0.01	

** Significant at 1 % level; * Significant at 5 % level ; ns non significant

II. Results of ANOVA for comparing specific gravity (air dry)

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	0.02	0.01	0.45^{ns}
Species	2	0.19	0.09	5.11*
Age x species	6	0.14	0.02	1.29^{ns}
Error 1	24	0.44	0.02	
Position within species	6	0.92	0.15	15.34**
Age x Position within species	18	0.27	0.01	1.51^{ns}
Error	48	0.48	0.01	

** Significant at 1 % level; * Significant at 5 % level ; ns non significant

III. Results of ANOVA for comparing specific gravity (Oven dry)

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	0.05	0.02	1.06^{ns}
Species	2	0.12	0.06	3.51*
Age x species	6	0.09	0.02	0.88^{ns}
Error 1	24	0.41	0.02	
Position within species	6	0.65	0.11	13.14**
Age x Position within species	18	0.24	0.01	1.60^{ns}
Error	48	0.39	0.01	

** Significant at 1 % level; * Significant at 5 % level; ns non significant

IV. Results of ANOVA for comparing tracheid length

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	7821178.29	2607059.40	5.84**
Species	2	906378.79	453187.40	1.01^{ns}
Age x species	6	4876445.37	812740.90	1.82^{ns}
Error 1	24	10718271.21	446594.63	
Position within species	6	31227212.14	5204535.40	17.17**
Age x Position within species	18	19505721.75	1083651.20	3.58**
Error	48	14549061.79	303105.45	

** Significant at 1 % level; ns non significant

V. Results of ANOVA for comparing tracheid diameter

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	133.60	44.53	1.00^{ns}
Species	2	1450.77	725.38	16.25**
Age x species	6	386.01	64.34	1.44^{ns}
Error 1	24	1071.54	44.65	
Position within species	6	801.76	133.63	4.10**
Age x Position within species	18	863.94	48.00	1.47^{ns}
Error	48	1566.26	32.63	

** Significant at 1 % level; ns non significant

VI. Results of ANOVA for comparing tracheid wall thickness

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	36.50	12.77	6.86**
Species	2	5.19	2.59	1.46^{ns}
Age x species	6	21.98	3.66	2.07^{ns}
Error 1	24	42.57	1.77	
Position within species	6	187.95	31.33	9.25**
Age x Position within species	18	46.02	2.56	0.76^{ns}
Error	48	162.51	3.39	

** Significant at 1 % level; ns non significant

VII. Results of ANOVA for comparing tracheid lumen diameter

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	288.60	96.20	1.44^{ns}
Species	2	1309.60	654.80	9.81**
Age x species	6	165.71	27.62	0.41^{ns}
Error 1	24	1601.34	66.72	
Position within species	6	56.81	9.47	0.20^{ns}
Age x Position within species	18	996.67	55.37	1.18^{ns}
Error	48	2260.99	47.10	

** Significant at 1 % level; ns non significant

VIII. Results of ANOVA for comparing Runkel ratio

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	0.55	0.18	3.23*
Species	2	0.17	0.09	1.51^{ns}
Age x species	6	0.10	0.02	0.29^{ns}
Error 1	24	1.36	0.06	
Position within species	6	1.55	0.26	4.02**
Age x Position within species	18	0.88	0.05	0.76^{ns}
Error	48	3.08	0.06	

** Significant at 1 % level; * Significant at 5 % level ; ns non significant

IX. Results of ANOVA for comparing shape factor

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	0.12	0.04	4.18*
Species	2	0.02	0.01	1.17^{ns}
Age x species	6	0.02	0.00	0.30^{ns}
Error 1	24	0.23	0.01	
Position within species	6	0.41	0.07	6.08**
Age x Position within species	18	0.16	0.01	0.80^{ns}
Error	48	0.54	0.01	

** Significant at 1 % level; * Significant at 5 % level; ns non significant

X. Results of ANOVA for comparing slenderness ratio

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	2773.42	924.47	2.75^{ns}
Species	2	2500.91	125.46	3.73*
Age x species	6	3228.71	538.12	1.60^{ns}
Error 1	24	8055.77	335.66	
Position within species	6	5990.51	998.42	5.10**
Age x Position within species	18	3950.00	219.44	1.12^{ns}
Error	48	9390.44	195.63	

** Significant at 1 % level; * Significant at 5 % level ; ns non significant

XI. Results of ANOVA for comparing coefficient of flexibility

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	732.23	244.08	3.97*
Species	2	190.57	95.29	1.55^{ns}
Age x species	6	131.50	21.92	0.36^{ns}
Error 1	24	1474.56	61.44	
Position within species	6	2664.66	444.11	6.00**
Age x Position within species	18	1027.53	57.09	0.77^{ns}
Error	48	3550.14	73.96	

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XII. Results of ANOVA for comparing coefficient of rigidity

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	732.23	244.08	3.97*
Species	2	190.57	95.29	1.55^{ns}
Age x species	6	131.50	21.92	0.36^{ns}
Error 1	24	1474.56	61.44	
Position within species	6	2664.66	444.11	6.00**
Age x Position within species	18	1027.53	57.09	0.77^{ns}
Error	48	3550.14	73.96	

** Significant at 1 % level; * Significant at 5 % level ; ns non significant

XIII. Results of ANOVA for comparing ray height

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	37157.80	12385.93	17.23**
Species	2	1704.80	852.14	1.19^{ns}
Age x species	6	11360.16	1893.36	2.63*
Error 1	24	17249.11	718.71	
Position within species	6	22153.65	3692.27	5.89**
Age x Position within species	18	6164.05	342.45	0.55^{ns}
Error	48	30112.15	627.34	

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XIV. Results of ANOVA for comparing ray width

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	30.57	10.19	1.31^{ns}
Species	2	137.20	68.60	8.79**
Age x species	6	125.08	20.85	2.67*
Error 1	24	187.19	7.80	
Position within species	6	46.20	7.70	3.04*
Age x Position within species	18	74.81	4.16	1.64^{ns}
Error	48	121.65	2.53	

** Significant at 1 % level; * Significant at 5 % level ; ns non significant

XV. Results of ANOVA for comparing tracheid frequency in earlywood

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	14549.75	4849.92	0.42^{ns}
Species	2	543866.54	271933.27	23.82**
Age x species	6	194356.48	32392.75	2.84*
Error 1	24	274004.63	11416.86	
Position within species	6	560731.25	93455.21	11.74**
Age x Position within species	18	93055.17	5169.73	0.65^{ns}
Error	48	382202.49	7962.55	

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XVI. Results of ANOVA for comparing tracheid frequency in latewood

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	98589.78	32863.26	1.39^{ns}
Species	2	281672.78	140836.15	5.96**
Age x species	6	580892.61	96815.43	4.10**
Error 1	24	567038.29	23626.60	
Position within species	6	434131.34	72355.22	13.53**
Age x Position within species	18	377687.36	20982.63	3.92**
Error	48	256694.97	53547.81	

** Significant at 1 % level; * Significant at 5 % level ; ns non significant

XVII. Results of ANOVA for comparing tracheid percentage in earlywood

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	11.65	3.88	0.52^{ns}
Species	2	6.43	3.21	0.43^{ns}
Age x species	6	88.38	14.73	1.98^{ns}
Error 1	24	178.56	7.44	
Position within species	6	49.20	8.20	1.05^{ns}
Age x Position within species	18	56.26	3.13	0.40^{ns}
Error	48	375.43	7.82	

ns non significant

XVIII. Results of ANOVA for comparing ray percentage in early wood

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	11.67	3.89	0.52^{ns}
Species	2	6.24	3.12	0.42^{ns}
Age x species	6	88.06	14.68	1.97^{ns}
Error 1	24	178.69	7.45	
Position within species	6	49.65	8.27	1.06^{ns}
Age x Position within species	18	55.61	3.09	0.40^{ns}
Error	48	374.96	7.81	

ns non significant

XIX. Results of ANOVA for comparing tracheid percentage in latewood

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	10.77	3.59	1.24^{ns}
Species	2	0.58	0.29	0.10^{ns}
Age x species	6	143.76	23.96	8.28**
Error 1	24	69.43	2.89	
Position within species	6	23.83	3.97	3.61**
Age x Position within species	18	33.58	1.87	1.70^{ns}
Error	48	52.83	1.10	

** Significant at 1 % level; ns non significant

XX. Results of ANOVA for comparing ray percentage in latewood

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Age	3	10.77	3.59	1.24^{ns}
Species	2	0.58	0.29	0.10^{ns}
Age x species	6	143.76	23.96	8.28**
Error 1	24	69.43	2.89	
Position within species	6	23.83	3.97	3.61**
Age x Position within species	18	33.58	1.87	1.70^{ns}
Error	48	52.83	1.10	

** Significant at 1 % level; ns non significant

XXI. Results of ANOVA for comparing cellulose content between species

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Between Species	2	294.497	147.248	12.411**
Error	6	71.185	11.864	
Total	8	365.682		

** Significant at 1 % level

XXII. Results of ANOVA for comparing lignin content between species

Source	Degrees of freedom	Sum of Squares	Mean Square	F
Between Species	2	49.863	24.931	9.059*
Error	6	16.512	2.752	
Total	8	66.375		

* Significant at 5 % level

EVALUATION OF WOOD QUALITY OF SELECTED TROPICAL PINES RAISED IN THE HIGH RANGES OF KERALA, FOR PULP AND PAPER MAKING

By

AJAYGHOSH, V.

ABSTRACT OF THE THESIS

Submitted in partial fulfillment of the
requirement for the degree

Master of Science in Forestry

Faculty of Agriculture
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DEPARTMENT OF TREE PHYSIOLOGY AND BREEDING
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2010

ABSTRACT

A study entitled "Evaluation of wood quality of selected tropical pines raised in the high ranges of Kerala, for pulp and paper making" was conducted in the College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur during the period 2008-2010. The objective of the study was to evaluate the wood quality of *Pinus caribaea Morelet*, *Pinus patula Schl. et Cham. and Pinus oocarpa Schiede* grown in research trials of the Kerala forest department in the high ranges of Idukki district of Kerala. Increment core wood samples were collected at breast height from trees, selected at random, from each plot representing each species belonging to different age levels. These samples were then subjected to intensive investigations to find out radial variation (pith, middle and periphery), species variation and influence of age on different wood physical, anatomical and chemical properties. The study revealed that many of the characters studied were influenced by species and age interaction. Radial variation was also found to have significant difference within the species for characters studied. As a whole, under the present climatic condition *P.caribaea* was found to perform better with wood properties within the accepted range suitable for pulping and paper making. On the other hand, *P. patula* and *P. oocarpa* were also found to be promising species for pulping and papermaking with better derived fiber ratios. However, *P. oocarpa* had specific gravity value slightly more than that is recommended for pulp and paper making. Studies on chemical composition revealed that *P. ooccarpa* had better performance with higher cellulose and lower lignin content. So what needs to be determined is the relationship, if any, between wood and tracheid properties of these species and the products which can be manufactured from this renewable resource. For this, more extensive study is needed for which the results of this study could be used as a base line data for future tree improvement aspects of these species with reference to wood quality and to bring out their potential utility for future afforestation programmes and timber utility.