WOOD PROPERTY VARIATION IN SELECTED CLONES OF *CASUARINA EQUISETIFOLIA* L. GROWN IN KARUR DISTRICT, TAMIL NADU FOR PULP AND PAPER MAKING

By

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2013

DECLARATION

I hereby declare that this thesis entitled "**Wood property variation in selected clones of *Casuarina equisetifolia* L. grown in Karur district, Tamil Nadu 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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Certified that this thesis, entitled **"Wood property variation in selected clones of *Casuarina equisetifolia* L. grown in Karur district, Tamil Nadu for pulp and paper making"** is a record of research work done independently by **Mr. Vishnu, R. (2011-17-105)** under my guidance and supervision and it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

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ACKNOWLEDGEMENT

With deep admiration I evince my heartfelt gratitude and unforgettable owe to my major advisor **Dr. E.V. Anoop**, Associate Professor and Head, Department of Wood Science, College of Forestry for his valuable guidance, support, inspiration, critical advise, encouragement and friendly cooperation throughout the course of my research work. I consider myself lucky to have him as my advisor.

I extend my wholehearted thanks to **Dr. A.V. Santhoshkumar**, Associate Professor and Head, Department of Tree Physiology and Breeding, College of Forestry and member of advisory committee for his keen interest and valuable suggestions he has provided throughout the course of my study.

I owe my sincere thanks to my advisory committee member **Dr. V. Jamaludheen**, Assistant Professor, Dept. of Silviculture and Agroforestry, College of Forestry for his cooperation and worthful advice extended to me during the study.

My earnest thanks are due to **Kannan C.S. Warrier**, Scientist-D, Division of Genetics and Tree Breeding, Institute of Forest Genetics and Tree Breeding, Coimbatore and advisory committee member for the whole hearted cooperation and intellectual advice to me during the course of study.

I take this opportunity to render my sincere gratitude to **Dr. K. Sudhakara**, Dean, College of Forestry for his constant support during the study.

I am wholeheartedly obliged to **Dr. T.K. Kunhamu**, Associate Professor and Head, Department of Silviculture and Agroforestry, College of Forestry for his timely advice and constant help in a way of extending the facilities available in the department for conducting the present study.

My deep sense of gratitude goes to **Mr. S. Gopakumar**, Associate Professor, Department of Forest Management and Utilization, College of Forestry; **Dr. P.O. Nameer**, Associate Professor and Head, Department of Wildlife Sciences, College of Forestry; **Dr. K. Vidyasagaran**, Associate Professor and Head, Department of Forest Management and Utilization; **Mr. K. Sreenivasan,** Assistant Professor, Department of Forest Management and Utilization for kindly providing me valuable advice and various facilities for the smooth conduct of the study.

Many thanks are due to **Dr. C.P. Reghu,** Senior Scientist (Germplasm), Rubber Research Institute of India, Kottayam for his guidance, cooperation and for making available the facilities at his disposal for conducting the experiment. I am also expressing my heartfelt thanks to **Smt. Sunandha,** statistician for her valuable guidance and timely help to carry out statistical analysis.

The help rendered by **Mr. Aadarsh, Ms. Anju, Ms. Saritha, Ms. Anu, Miss. Divya, Mr. Prasanth, Mr. Nishad and Ms. Manisha,** in helping me during thesis work is also remembered with gratitude.

Words cannot really express the true friendship that I relished with **Mr. Anish, Mr. Sreejith Babu, Mr. Nijil, Mr. Anoop, Mr. Kiran, Mr. Reneesh, Mr. Jiljith, Ms. Parvathy, Ms. Surya, Miss. Mereena, Ms. Sukanya and Ms. Remya** for the heartfelt help and back-up which gave me enough mental strength to get through all mind-numbing circumstances.

The constant support and help from my seniors and junior friends, staffs will always be remembered.

I am extremely grateful to **Institute of Forest Genetics and Tree Breeding, Coimbatore** for giving me valuable data and samples for this study.

At this juncture, I express my deep love to my **parents** and my **sister** without whose moral support, blessing and affection this would not have been a success.

Above all I bow my head to **THE ALMIGHTY** whose blessings enabled me to undertake this venture successfully.

VISHNU, R.

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DEDICATED TO
MY PARENTS AND TEACHERS

INTRODUCTION

INTRODUCTION

Wood is an important natural resource, one of the few that are renewable. It has a complex polymeric structure consisting of lignin and carbohydrates, which form the visible lignocellulosic structure of wood, and confers it the suitability as a raw material for solid wood products such as lumber, plywood, and wood pallets, and for pulp and paper production. The demand of wood and wood products has been increasing tremendously worldwide due to population growth and shrinkage of forest and plantation area. Global demand for wood is increasing at an annual rate of 1.7 per cent (South, 1999). The developing countries are confronted with the problem of shortage of long fibred wood pulp to meet the demand of its pulp and paper industry. The consumption of paper products are on the rise in the country despite technological advancements in various fields. The pulp and paper industry is a principal chemical industry relying upon wood for its production process. In view of the increasing demand of wood as raw material for pulp and paper industry, various materials of plant origin have been tested time to time. At the same time, resources from natural and planted forests are insufficient to meet the demands. The scope for expansion of area is also limited (Gregory *et al.*, 2002). Many plantations of exotic and indigenous species have been established in India to meet this enhanced requirement of raw materials for pulp and paper. In view of the increasing demand for wood by paper industry, plantations of fast growing tree species managed under short rotations having a growing importance for the sustainability of industrial wood raw material have been raised.

The Institute of Forest Genetics and Tree Breeding (IFGTB) and other institutes have initiated several tree improvement trials of fast growing hardwood species such as casuarina (*Casuarina equisetifolia* L.) suitable for pulping. Genetic improvement of *Casuarina spp.* through selection and breeding is a flagship program of IFGTB for over two decades. In order to widen genetic base of clones used in farm forestry, IFGTB conducted clonal testing with a large collection of clones. As the part of this, three clonal trials were established namely (1) Mayiladumparai, near Kulithalai, Tamil Nadu (Inland, red soil), (2) Moorthipalayam, near Karur, Tamil Nadu (Inland sodic soil) and (3) Singramam, near Cuddalore, Tamil Nadu (Casuarina growing zone). Currently IFGTB is trying to evaluate and characterize these clonal trials with reference to yield, tree form, biomass, pulping characteristics and key nursery pests. Based on analysis of growth performance, three clones, clone 47, clone 56 and clone 60 were shortlisted. As the part of IFGTB project, the billets of *Casuarina equisetifolia* L. clones (3 years age) were collected for this study from the clonal plantation of Karur district, Tamil Nadu, for selecting the best suitable clone for pulp and paper industry.

Casuarina equisetifolia L. is indigenous to the tropics and subtropics of Southeast Asia and Western Pacific regions, including northern Australia (Ogata *et al.*, 2008). An important species of the family *casuarinaceae* is widely planted along the coastal areas of India. The wood is mainly used for firewood, poles, construction and pulping (Guha *et al.*, 1970a; Varghese and Sivaramakrishna 1996). Casuarina is considered an important multi-purpose tree on account of its utility in nitrogen fixing, wind breaks, soil erosion control, suitability for fuel wood, poles, pulp and paper production etc. The suitability of wood for paper pulp makes it as a promising raw material for the manufacture of paper for writing, printing and wrapping. It can also be used to prepare hard boards and chip boards. In order to understand the possibility of casuarina wood as raw material for pulp and paper production, scientific knowledge on anatomical and chemical property of the wood is important. To use its wood for pulp and paper production most effectively requires knowledge of not only the amounts of various substances that make up wood, but also how those substances are distributed in the cell walls. Because of the great structural variations in wood, there are many possibilities for selecting a species for a specific purpose.

The most striking feature of wood, unlike other natural materials, is its high degree of variability (Zobel and Van Buijtenen, 1989). Understanding variation in anatomical properties of wood of any species is imperative in its breeding program as well as for good utilization, since variation in wood density or strength is mainly due to differential expression of anatomical properties (Zobel and van Buijtenen, 1989). The main reason for the pulp and paper industry's very limited use of tropical broadleaved wood species is the wide variation of densities, fibre dimensions and other characteristics of the sometimes hundreds of wood species in a stand. In general, variation in the wood of species such as *C. equisetifolia* has received little attention (Chowdhury *et al.*, 2007). Previous studies have dealt with a few anatomical properties (El-Osta *et al.*, 1981; Varghese and Sivaramakrishna 1996; Chowdhury *et al.* 2009b), but not in relation to physical and mechanical (density and/or compressive strength) properties. The present study compares the suitability of clones of casuarina wood for pulp and paper making by analyzing its variation in physical, anatomical and chemical properties.

Objectives:

The objective of the present study titled "Wood property variation in selected clones of *Casuarina equisetifolia* L. grown in Karur district, Tamil Nadu for pulp and paper making" is to find out:

1. Inter-clonal variation in physical, anatomical and chemical properties of *Casuarina equisetifolia* L.
2. Variation in factors like Runkel ratio, shape factor, rigidity coefficient, flexibility coefficient, and slenderness ratio which have application in paper and pulp industries.
3. Suitability of clones for pulp and paper making.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Wood is a highly variable renewable natural resource. Generally, all dimensional and physical characteristics of wood within a tree exhibit a high range of variation (Panshin and de Zeeuw, 1980).

2.1 THE SOURCES OF VARIATION IN FOREST TREES

Zobel and Talbert (1984) defined variation at a number levels or sources 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 are; (i) Within ring differences; (ii) Changes from the centre (pith) to the outside (bark) and (iii) Differences due to different heights (Zobel and van Buijtenen, 1989).

2.1.1 Importance of understanding variation in forest trees

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).

2.1.2 Hardwood variation

The woods of hardwoods and softwoods differ greatly from each other. Hardwoods possess more complex wood than softwoods, having very short and large diameter vessel elements, fibres (fibre tracheids), longitudinal parenchyma, and rays with differing types of cells (Mac Donald and Franklin, 1969). Wood properties of hardwoods usually have the same overall pattern as conifers, varying greatly from tree to tree within a species and sometimes also considerably with the geographic range where the species originated or where it was later grown as an exotic (Zobel and Van Buijtenen, 1989). Most of the studies pertaining to hardwoods were to find variation related to radial direction and confined to fiber length and vessel element length and occasionally specific gravity (Panshin and de Zeeuw, 1980; Zobel and Sprague, 1998). Works pertaining to variation in length of hardwoods fibers and vessel elements were reviewed by Dinwoodie (1961), Panshin and de Zeeuw (1980), and Zobel and van Buijtenen (1989). Knigge and Koltzenburg (1965) found a rapid increase in cell length the first 10 to 20 years in hardwoods, followed by a leveling off. This pattern was also present in *Populus spp.* (Boyce and Kaiser, 1961), *Eucalyptus spp.* (Bisset and Dadswell, 1949), and *Liriodendron spp.* (Thorbjornsen, 1961). Vessel length continued to increase with ring number from tree center, according to Knigge and Koltzenburg (1965), who report that the changes in cell characteristics occur at all heights in the tree, and that they depend on the distance from the pith.

The variability in wood anatomical characteristics has profound influence on the properties of wood (Dadswell, 1958; Burley and Palmer, 1979). Features of interest in this connection include cell size, proportion and arrangements of different elements and specific gravity. The general pattern of variation in wood element dimensions is found not only within a species but also observed within a tree (Dinwoodie, 1961; Rao and Rao, 1978; Pande *et al.*, 1995). Most trees have a pattern in wood qualities from the center of the tree to outwards, from the base to the top of the trees and within an annual ring (Sluder, 1972). Though different types of wood variation is present in hardwoods, inter- tree variation, intra- and inter clonal variation and provenance variation are relevant with respect to present study.

2.1.2.1 Inter-tree variation

Significant variation among trees was reported in basic density, fiber and vessel element length by Chowdhury *et al.* (2009). He suggested in his study that considerable variation in wood properties among tree were of sufficient magnitude and could provide an opportunity to select tree for breeding programs to improve the wood quality. Gartner *et al.* (1997) studied variation in anatomy and specific gravity of wood within and between trees of *Alnus rubra.* He found significant variation in several characteristics between trees (specific gravity, vessel diameter), although the magnitude of these difference were not large.

Pande *et al.* (2008) studied within and among tree variations in physico-chemical and anatomical properties of seed raised plantation wood of *Leucaena leucocephala* had been investigated. Within tree variation in specific gravity, fibre length and Runkel ratio were significant due to height. The variation in anatomical properties and ratios in radial direction were non-significant. Inter-tree variations for wood anatomical properties were significant and accounted for genetic variability in trees for wood traits. Site quality also affected anatomical properties and pulping and paper quality ratios significantly. Lignin content (%) significantly varied with reference to height and also shown significant inter-tree variation. Lignin content was significantly positively correlated with fibre wall thickness. Extractives had shown non-significant intra and inter-tree variations. Most of the anatomical characters showed significant positive correlation to each other. Vessel member dimensions showed significant negative correlation with specific gravity. Inter-tree variations for wood anatomical properties were significant and accounted for genetic variability in trees for wood traits. Location also affected anatomical properties and pulping and paper quality ratios significantly.

2.1.2.2 Intra and inter clonal variation

A number of studies have dealt with intra and inter clonal and provenance variations of wood properties of different species. Researchers have analyzed anatomical variation in wood elements within and among clones such as *Populus spp., Eucalyptus spp., Dalbergia spp.* in order to assess wood quality. (Phelps *et al.* 1982; Kauba *et al.,* 1998; Rao *et al.,* 2002; Pande and Singh, 2005).

Beaudin *et al.* (1992) studied inter-clonal, intra-clonal and within tree variation in wood density of hybrid poplar. Twenty-eight nine-year-old trees from ten clones of the hybrid *Populus euramericana* in south-central Quebec were selected to determine the pattern of wood density variation within stems, within clones, and between clones. He found that all the measured anatomical properties varied significantly across sites. Clonal variation was highly significant for all the anatomical properties studied. The variation in radial pattern was characterized by a rapid increase in the first few years in fibre length, width, and proportion, wall thickness, and percent cell wall area. Ray proportion remained constant, whereas the vessel lumen area and proportion decreased with cambial age. Clones, trees, and heights have a highly significant effect on wood density. The wood density of this hybrids tend to be high at the bottom of the tree, decreases to a minimum at mid-height, then increases again near the top of the merchantable stem.

According to Matyas and Pezlen (1997), wood properties vary greatly within and among poplar trees. They found only slight changes in the radial distribution of vessel lumen, fibre lumen, and cell walls in poplar clones. Within tree variation in anatomical properties in hybrid poplars was studied by Holt and Murphey, 1978; Murphey *et al.*, 1979; Yanchuk *et al.*, 1984; Bendtsen and Senf, 1986; Kauba *et al.*, 1998). These studies found significant clone and longitudinal variation in fibre length.

Genetic variation in wood specific gravity in poplar from two locations in Punjab was studied by Dhillon and Sidhu (2007). Significant differences among clones were reported at both the locations. Specific gravity ranged from 0.40 to 0.47 in central plain region and from 0.36 to 0.44 in the semi-arid region. Genotype × environment interaction was also found significant. Song *et al.* (1997) noticed significant difference in wood density of trembling aspen (*Populus adenopoda*) among four locations in China. Clone × environment interaction was also found to be significant.

The variability of wood density and fiber length was determined in six 13-year-old willow clones growing under different site conditions in Argentina. Site influence was reported to be significant for basic density, which ranged from 0.364 kg/dm^3 and 0.455 kg/dm^3. For fiber length, values of the continental site were significantly higher. Mean value for each clone varied between 837.1μm and 1142.1 μm. They concluded in their study that heritability values showed strong genetic control for density (h^2=0.65) than fiber length (h^2=0.32) (Monteoliva *et al.*, 2005).

Wood density and fiber length in 9-year-old populus clones grown in an intensively cultured plantation in western Washington were studied in relation to clone age, growth rate and pruning (DeBell *et al.*, 2002). Averaged over all trees, fiber length increased from 0.57 mm at age one to nearly 1.0 mm at age nine. Averaged over all disks at 1.5 m, clones differed significantly in ring width, and fiber length. Mean values for two wood properties at 3.0 m were slightly lower than those at 1.5 m and did not differ significantly among clones. Within clone correlations between ring width and fiber length or between wood properties were low, and generally non-significant.

Pande and Singh (2009) studied individual tree, intra- and inter-clonal variations in wood properties of the clonal ramets of *Eucalyptus tereticornis* Sm. They found that inter-clonal variations and intra-clonal were significant along radial directions. The values of Runkel ratio, shape factor and fibre-length to diameter ratio of the selected clones from Lalkuan (Uttarakhand) were well within the permissible limits for producing better pulp. The wood properties of the clones were comparable with the clones of ITC- Bhadrachalam grown in south India except for fibre-length, Runkel ratio and shape factor which were significantly higher in south India. ITC-Bhadrachalam clones grown in Bannakhera and Lalkuan were not different from each other on the basis of wood anatomical properties.

Inter and intra-ramet variation in wood traits of micro propagated L-34 clone plantation of *Populus deltoides* was studied by Gautam and Pande (2008). Fiber diameter and vessel diameter significantly vary for different ramets, whereas variations were non-significant for fiber length, wall thickness and vessel element length. Non-significant differences in most of the wood element dimensions for height, direction and location showed homogeneous wood properties within the ramets of L-34 clone. Significant intra-clonal variations for vessel element diameter and fiber diameter showed that these characters were not controlled in micro-propagated plantation wood of L-34 clone while, important characters like fiber length, wall thickness and specific gravity were well controlled in L-34 clone.

Pande and Singh (2005) studied within tree, inter-clonal and intra-clonal variations in specific gravity and wood anatomical properties of 8-year-old grown ramets of *Dalbergia sissoo* Roxb. Radial and location-wise intra-clonal variations were non-significant for anatomical properties and specific gravity for all six clones at all three sites. However, inter-clonal variations in wood anatomical properties and specific gravity were significantly different. Inter-clonal variations in anatomical properties and specific gravity were also significant due to sites. Within tree variations in anatomical properties like fiber length, fiber diameter, wall thickness, vessel member length and vessel member diameter due to vertical or radial direction and location (pith to periphery) were non-significant. Radial direction, location and height showed no impact on wood element variation. It indicated that there is no impact of juvenile wood, sapwood and heart- wood ratio, and reaction wood on wood anatomical properties of 8-year-old ramet of D. sissoo. It further indicated that clone raised ramet of 8-year-old *D. sissoo* showed the characteristics of mature wood. Within tree variations in specific gravity were significant due to height, which may be related to differential sapwood and heartwood ratio in the vertical direction. Different wood elements viz. fiber length, fiber diameter, wall thickness, vessel member length and vessel member diameter showed significant correlations with each other and with specific gravity.

2.1.2.3 Provenance variation

Influence of provenance variation on wood properties of *Tectona grandis* from the Western Ghats region in India was studied by Bhat et al (2004). Three major teak provenances were characterized in terms of mechanical and anatomical wood properties within the same age of 21-year-old plantations. Wright *et al.* (1994) revealed the provenance variation of stem volume and wood density of *Pinus caribaea* var. hondurensis growing at two locations in Queensland, Australia. The trials were established at ten locations. Assessments at two of the trials were carried out in 1973 and in 1979 to determine volume under Bark and wood density. Within sample variation and dry matter index were also analyzed with these two trials. The result showed significant differences ($p<0.05$) for VAR, VUB and DMI at Beerburrum as well as for VAR at Byfield. The thirteen provenances common to both locations produced 23% more VUB at Beerburrum. The Queensland selections included in the trials were superior for VUB production relative to the majority of the introduced provenances.

Morales (1987) studied wood specific gravity of 220 species from two tropical forests in Mexico. Half of them were from a tropical rainforest, half of them were from a tropical deciduous forest. The two groups were compared using a Student's t-test. Highly significant differences were found in specific gravity between the species from two areas. Specific gravity of the wood showed considerable differences between species within each region and between two regions. The trees from the drier region showed a higher average density (average

0.78) than that of trees from the more humid region (average 0.58). Bass *et al.* (1983) stated that in the arid flora of Israel, vessel element tend to have thicker walls, smaller diameter, and be more crowed characters that would lead us to expect a higher specific gravity in the wood species from that region.

Provenance variation in two species viz. *Acacia auriculiformis* and *Acacia mangium* were examined by Khasa *et al.* (1995a) in four test sites in Zaire. Significant provenance differences existed in all morphological traits as well as woods specific gravity. In another study by Khasa *et al.* (1995b), wood density of the above two species were compared with those of *Eucalyptus urophylla*, *Cassia siamea* and *Leucaena leucocephala* across the same our sites in Zaire. Both sites and species effect were found to be significant in this study.

Provenances variation in fiber-length in *Acacia mangium* was studied by Sining (1989) in Sabah. Fiber length and length/width ratios were recorded for plantations of *A. mangium* and *A. auriculiformis* by Ku and Chen (1984). Fiber dimensions and ratios were compared by Varghese *et al.* (1999) for plantation grown *A. mangium, A. auriculiformis and A. crassicarpa* from Thane, Maharashtra. *A. crassicarpa* had long fibers and vessel-elements. Three years old *A. auriculiformis* trees were studied for fiber length, lumen diameter, wall thickness and Runkel ratio by Kholik and Marsoem (2002) and in mangium (*A. mangium*) wood by Sahri (1993). In a study on teak (*Tectona grandis*), Nair and Mukerji (1957) found large differences in specific gravity and strength properties of trees from different areas, whether natural or planted. Boone and Chudnoff (1970) found similar provenance variation in specific gravity of mahogany (*Swietenia macrophylla*). They obtained very dense wood (0.9) from southern Mexico and Nicaragua and a lower density (0.7) from Guatemala and Costa Rica.

2.1.2.4 Axial variation

The effect of height on wood properties is equally variable as it is in conifers. Many trees have wood properties that vary at differing heights in the tree. A change in wood properties with height is automatic since the proportion of juvenile wood in the stem increases extensively from the base to top (Zobel and van Buijtenen, 1989).

2.1.2.4a Axial variation in specific gravity

Differences in specific gravity are mostly a direct result of proportion of top wood, which consists of juvenile wood (Zobel, 1975). Since the proportion of juvenile wood in the stem increases from base to top, specific gravity also increases from base to top. A study on physical and mechanical properties of *Grevillea robusta* by Kamala *et al.* (2000) found significant variation for specific gravity with height. Results also indicated that average specific gravity increases with height. An increase in density with height was observed in eucalypts and populus (Dargavel, 1968; Skolman, 1972; Taylor, 1973). Variation of wood specific gravity from the base to top of the tree was investigated in *Gmelina arborea* in Venezuela by Espinoza (2004). In the study, increment cores were taken from thirty trees at five different sections up the stem. These trees were chosen from commercial plantation located at three different sites. The results showed that there was a decrease in specific gravity from stump to half of the total height then increased towards the top of the stem. No correlation was found between specific gravity and height. Lindgren (1951) reported that the much higher specific gravity and lower moisture content of freshly cut butt logs compared to top logs.

Variations in specific gravity were found significant in different clones of *Delbergia sissoo* (Pande and Singh, 2005). The higher value for specific gravity was noticed at breast height, thereafter it declined and again increased to the top. Similar studies in *Swietenia macrophylla* (Briscoe *et al.*, 1963), *Liriodendron tulipifera* (Taylor, 1968), *Populus tremuloides* (Einsphahr *et al.*, 1972; Yanchuk *et al*, 1983a, and *Liquidambar styraciflua* (Webb, 1964) showed a high density at base, a decrease for some distance up the tree, followed by an increase toward the merchantable height. In this study they found significance difference in specific gravity due to height within a ramet. They found that height has an impact on specific gravity due to differential sapwood and heartwood ratio.

2.1.2.4b Axial variation in fibre morphology

Anatomical parameters of wood quality such as fibre characteristics, vessel frequency and diameter and proportion of tissues were examined in 8 year old trees of six *Populus deltoides* clones growing in plantations. Statistical analyses were conducted to determine clonal variations and effect of age on anatomical properties. The analysis indicated significant clonal variation in specific gravity, fibre length vessel length, fibre diameter, lumen diameter, vessel frequency and vessel diameter. Specific gravity, fibre length and vessel length also show an increase with age. Specific gravity has been found to be positively correlated with fibre length in all the clones but with vessel diameter only in 4 clones (Chauhan *et al.*, 1999).

Vertical variation in wood fiber dimensions was observed by other workers. Along the axis of stem or branch, the decrease in fiber length from the base to 50% and 70% of the stem height or branch length observed by Bhat *et al.* (1989) in their study on fiber length variation in stem and branches of eleven tropical hardwoods. Dimensional variation was investigated in fiber along vertical and horizontal axes of a 40-year-old tree of *Afzelia africana* felled in Gerei forest Nigeria by Idu and Ijomah (1996). Mean dimensional values were: fiber length 1116.23 µm, fiber diameter 21.94 µm, lumen diameter 11.8 µm, fiber wall thickness 5.55 µm, Runkel Ratio 0.98, flexibility coefficient 0.5, relative fiber length 50.56, vessel length 194.02 µm. Fiber length varied significantly on both axes investigated (showing patterns of alternate increase and decrease with increasing height and distance to pith), while fiber diameter and lumen diameter varied significantly only along vertical axis. Other traits analyzed showed considerable variation but were not significantly related to distance along either axis. In an analytical study on cell size variation in *Acacia nilotica*, Iqbal and Ghouse (1983) concluded that the length of vessel segments decreased from base to top and later stabilizing in the old trunk. Length of xylem fibers after an initial increase became more or less constant. Variation in fiber-length and cell wall percentage along the height of the tree was studied in *A. mangium* and *A.*

auriculiformis trees by Wu and Wang (1988). Variation was generally less in *A. auriculiformis.* Similar studies were also made by Ku and Chen (1984) in the above two Acacia species. The variability of fiber length in wood and bark in ten trees of *Eucalyptus globules* from three different locations within Portugal were studied by Jorge *et al.* (2000) The axial variation was small and in wood and bark; fiber length decreased in the wood and increased in the bark from the base to the top.

2.1.2.4c Axial variation in vessel morphology

The variation in all vessel dimensions showed no significant relationship with tree height in 1-214 poplar clones in Beijing (Jiang *et al.,* 2003). Dimensional variation was investigated in vessel characters along vertical and horizontal axes of a 40-year-old tree of *Afzelia africana* felled in Gerei forest Nigeria. Mean dimensional values were: vessel diameter (233.46 µm) and F/V length ratio (2.25). Variation in dimensions from stem base to the top in trees of "aroeira" (*Myracrodruon urundeuva*) was reported by Florsheim *et al.* (1999). Discs were removed from each tree at the base, breast height and 50% and 100% of commercial height. Samples were taken from each disc at 0%, 50% and 100% of the radius. In the longitudinal direction the lowest value of vessel length was found at the base, while the highest was found at 50% of commercial height.

Hudson *et al.* (1997) studied the vessel frequency variation among the clones of *Eucalyptus spp.* The similar result was later described by Leitch (2001) on four-year-old *E. globulus* trees at 15% of the total height; and by Leal *et al.* (2003) on twenty-seven-old *E. globulus* clones of 7 years age. Values for vessel coverage reported by Leitch (2001) and Leal *et al.* (2003) were between 8–12%, similar to the range obtained in a study by Ramirez *et al.* (2009). The results of this study showed an important variation on vessel area among the clones analyzed, which differ from those presented by Leal *et al* (2003) who have pointed out that vessel area remained rather constant for all clones. According to Fan *et al.,* (2009) vessel density usually increased with height on the trunk, especially inside the crown. There was a marked increase (1.5–3.2 times) in the vessel density (the number of vessels per wood area) moving from trunk to twig in the eight angiosperms.

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 to be correlated to properties utilized during the production of paper, and properties of the final product. 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. 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.

The importance of specific gravity has been emphasized by many investigators. Most pulp and paper properties are directly related to wood specific gravity (Barefoot *et al.*, 1965; Artuz-Seigel *et al.*, 1968). Wood density and ring width are the most commonly used indicators of wood material, quantity and quality. Wood density is considered the best single index for overall wood quality as well as pulp yield and quality (Bendtsen, 1978). The wood specific gravity is a useful indicator of the basic strength of wood (Shirin *et al.*, 1998). It is the sum total of the wood substance proper, extraneous matter and water content (Sekhar and Negi, 1966). The common methods of determining specific gravity are described in the Indian Standards (IS 1708: 1969). Among the various wood quality parameters, specific gravity is the most widely studied. 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 (Davis, 1961; Barefoot *at al.*, 1970; Lewark, 1979) and because it can be changed by silvicultural manipulation (Williams and Hamilton, 1961) and genetic manipulation (Zobel, 1961; van Bujijtenen 1962).

Wood density is one of the important factors that determine the economic utility of wood for paper and pulp making (van Buijtenen, 1982). 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. Wood density correlated with strength properties of wood, pulp yield and pulp quality (de Guth, 1960). Wood density is the best single descriptor of wood: it correlates with numerous morphological, mechanical, physiological, and ecological properties (Jerome *et al.*, 2006).

A study aimed at examining 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 pine. *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.

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 (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) stated 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).

Many solid-wood quality traits such as hardness and strength could be positively correlated with both tree age and basic density. Denser wood contains more wood per unit volume and tends to give a higher yield of pulp in paper manufacturing. Overall wood density typically increases with tree age as the proportion of lower-density material formed early in a tree's life is reduced by the formation of higher-density material in older trees (e.g. de Silva *et al.*, 2004).

2.2.2 Fibre morphology

Fibre length is a very important wood property. Investigations of relationships between the morphology of fibers and paper properties began in the early 1900's. However, results have often been contradictory. One of the first fiber properties related to paper strength properties was fiber length. Several investigators found that fiber length directly affects the tensile strength of paper. 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. Several investigators have found contradicting evidence that suggests fiber length does not have a great influence on paper properties, especially on tensile strength (Horn, 1974).

The analysis of fibre characteristics such as fibre length, fibre diameter, lumen width, cell-wall thickness and their derived morphological factors became important in estimating pulp quality of fibre (Dinwoodie, 1965; Amidon, 1981; Wood, 1981). One of the first fibre properties related to strength properties was fibre length. Several investigators found that extensibility of the bonding sites is a function of the fibre length (Horn, 1974; Wangaard and Woodson, 1973). This led to the conclusion that hardwood pulps are lower in paper strength because of their shorter fibres than those of softwoods with longer fibres. Other anatomical features like lumen size and cell wall thickness affect the rigidity and strength properties of the papers made from the fibres (Panshin and de Zeeuw, 1980). Fibres with large lumen and thin walls tend to flatten to ribbons during papermaking with enhanced inter-fibre bonding between fibres and consequently having good strength characteristics (Oluwadare, 1998).

In pulp manufacture, strength characteristics are determined in part by fibre length. Increased fibre length leads to the production of paper with increased strength. Bond strength is attributed to contact between the fibres and the adhesion capabilities of the surfaces, which are dependent upon fibre length, perimeter and coarseness. Also, during the manufacturing process, increased fibre length increases the strength of wet webs enabling easier handling (Seth, 1995). However, long fibres are not desirable for all applications. In some cases, shorter fibres are preferable, such as in the production of smooth-surfaced papers. Fibre properties differ between species, and consequently particular species have been limited historically to particular applications. Fibres from hardwood species are generally much shorter than those from softwoods. This results in the production of pulp and paper with desirable surface characteristics such as smoothness and brightness, but with low strength characteristics. In practice, where a single species providing fibre with an appropriate combination of characteristics has not been available, the mixing of long and short fibres from different species is used. If a single source were available, possessing the desirable characteristics plus optimal fibre length, this would be of great benefit to the processor.

Tracheid length in conifers and fibre length in hardwood is the cell dimensions next importance to wall thickness in determining the use of wood and quality of final product (Megraw, 1985). Many workers have since then studied the problem of variation in length of tracheids and fibres in the secondary xylem of softwoods and hardwoods. Work pertaining to variation in length of hardwood fibres and vessel elements were reviewed by Dinwoodie (1965), Panshin and de Zeuw (1980), Zobel and Van Buijtenen (1989).

Tensile and bursting strength were influenced primarily by cell wall thickness. Fiber length was important in so far as a minimum length is required for bonding and stress distribution. Tearing strength of unbeaten pulps was influenced primarily by fiber cross-sectional area and cell wall thickness; fiber cross sectional area had slightly greater influence than wall thickness (Horn, 1974). For fiber wall thickness, results showed that it remains constant for all trees across clones. Wood fiber morphology and wood chemistry are important traits because they determine key paper qualities such as strength, opacity, porosity, and bulk (Ramirez *et al.*, 2009).

A study conducted by Oluwadare and Ashimiyu (2007) showed that fibre characteristics and their morphologies significantly influenced the strength properties of the pulp sheet of *Leucaena leucocephala*. However cell-wall thickness and fibre length had the greatest influence on the strength properties of the unbeaten pulp. Fibre length was important in as much as minimum length is required for bonding ages distribution once beating commences.

The suitability of wood for particular purpose is determined by the variability in one or more of wood properties. In order to determine suitability of wood for pulp and paper making, many studies have been carried out by various researchers all over the world. A study on eucalyptus by Kibblewhite *et al.* (2000) reported that, there were substantial and often significant differences in various fibre dimensions between species and between the 8-year-old and 11-year-old material. *Eucalyptus maidenii* had longer fibres than *E. nitens* and *E. globulus* of the same age, and the fibre length of its 11-year-old samples was longer than the 8-year-old. The 11-year-old *E. maidenii* also had fibres of larger perimeter, much greater wall thickness, and correspondingly larger wall area than *E. globulus*, which itself was higher in these dimensions than *E. nitens*. The width thickness ratio, indicating fibre collapse potential, was highest for both *E. nitens* samples and equally low for 11-year-old *E. globulus* and both ages of *E. maidenii* samples.

The 11-year-old *E. maidenii* sample stood alone because it had the longest fibres of largest perimeter, wall thickness, and wall area of the six species/age pulps.

A study by Fan *et al.* (2009) showed that four of the fourteen sampled angiosperm trees and two of the seven conifer trees exhibited a uniform linear increase of lumen diameter with distance from the top to the base of the trunk. Lumen diameter did not vary axially in one angiosperm. In the remaining fourteen trees, conduit lumen diameter increased basipetally from the top of the crown and then stabilized near the base of the crown, or increased more slowly downwards (Fan *et al.,* 2009). Density, another key timber property, is known to be almost totally controlled by the fibre characteristics in diffuse porous woods. It was revealed that a significant positive correlation exists between density and fibre length and fiber wall thickness, and fibre diameter and properties of fibre in *Michelia chmapaka* Linn. (Purkayastha *et al*., 1974).

Various studies have discussed wood and fibre quality of eucalyptus. Clarke *et al.* (1997) studied a variety of wood characteristics including the average density, fibre length and chemical composition of nine eucalyptus species in three provenances from established trial sites in South Africa. These authors revealed significant differences in density, fibre length and chemical composition between the species and between sites. Naidoo *et al.* (2006) found a negative correlation between moisture availability and wood density and vessel amount in *Eucalyptus grandis* in the warm temperate region of South Africa. Miranda and Pereira (2002) studied the differences in wood density, fibre morphology, chemical composition and pulp yield in four provenances of *Eucalyptus globulus* at three different sites in Portugal. Their findings suggest no significant effect of provenance and site on the wood density. However, provenance and site caused significant variation in fibre length, cell wall thickness and lumen diameter (Klash *et al*, 2010).

In addition to these basic fibre dimensions, many studies indicated that indices (slenderness ratio, Runkel ratio and flexibility coefficient) which are deriving from fibre dimensions are also essential for pulp and paper industries.

Horn and Setterholm (1990) reported that the increase in raw material fiber length enhances the tearing strength of hardwood pulps. Saikia *et al.* (1997) and Ogbonnaya *et al.* (1997) succeed in evaluating the suitability of various non-wood fiber raw materials for pulp and paper manufacture by using those derived indices. Fibers with long length, high slenderness ratio (>33) and low Runkel ratio (<1) are fundamental in pulping and papermaking.

2.2.3 Vessel morphology

Hardwood pulps sometimes produce paper with poor printing characteristics because the vessels are "picked" from the paper during some kinds of printing, resulting in a non-uniform paper surface which affects the distribution of ink. (Brown and Panshin, 1940; Colley, 1973).

2.2.4. Ray morphology

Ray cells also influence the quality of both solid wood and pulp products. The ray and parenchyma cells themselves are thin-walled and very short and contribute little to the strength properties of paper, although they provide smoother sheet. Just as for vessels, there is interest in trees with a lesser amount of ray cells because of their variability and adverse effect upon specific gravity, yield of paper, and strength of boards (Zobel, 1989).

2.2.5 Cellulose content

Cellulose is one of the many important polymers in plants. Cellulose is made 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).

Mahmood (1993) studied alphacellulose content of wood collected from trunk and branches of *Casuarina equisetifolia.* In trunk wood alpha cellulose content was 46.41±4.49 whereas in branch wood it was 42.87±2.66. Fang *et al.* (1995) studied biomass production and pulp making performance of a *Metasequoia glyptostroboides* plantation. He found that the average cellulose content was 47.5% and the average fibre length was 3.175 mm. So *Metasequoia glyptostroboides* is suitable as raw material for pulp and paper industry.

2.2.6 Lignin content

Lignin is a complex and irregular poly-phenylpropanoid heteropolymer present in the cell walls of vascular plants (Boerjan *et al.*, 2003). It enhances the structural integrity of the cellwall and stiffness of the stem and roots. It has long been recognized that lignin distribution influences almost all processes in which wood is converted to paper (Westermark *et al.*, 1988). The presence of lignin is generally regarded as undesirable by the pulp and paper industries, primarily because it is responsible for the yellowing of paper based products over time if not effectively removed. The industry expends numerous energy and resources removing lignin with a variety of chemical pulping and bleaching processes (Fromm *et al.*, 2003). The effective use of fibrous resources for industrial purposes is in fact largely dependent on the extent to which the plant cell wall is lignified. (Maa *et al.*, 2011)

Mahmood (1993) showed that lignin content was 26±3.71 and 27.73±1.55 respectively in trunk wood and branch wood of *Casuarina equisetifolia.* In a study conducted by Jahan *et al.*, (2007) on *Acacia auriculiformis* grown in Bangladesh, showed that the lignin content in *A. auriculiformis* was 19.4% and alpha -cellulose 44.1%, which was within the range of other acacias, but that of extractives was higher.

In a study on the difference of chemical properties among five acacia species woods by TeFu and LuoHua (2005) compared the chemical composition of five acacia wood species: *A. auriculiformis, A. crassicarpa, A. cincinnata, A. mangium* and *A. melanoxylon*. The ash, holocellulose, alphacellulose, 1% NaOH extractive, benzene-ethanol extractive, pentosan, lignin and relative crystallinity contents were analyzed. Results showed significant differences in the chemical composition of the five Acacia species.

The study of chemical composition of Eucalyptus showed significant difference in klason lignin among clones. Extractives and lignin have generally been found to correlate negatively with pulp yield, whereas the carbohydrate fractions, as α-cellulose correlates positively with pulp yield.

2.3. SUITABILITY OF *CASUARINA EQUISETIFOLIA* L. FOR PULP AND PAPER MAKING

Casuarinas are important multipurpose species distributed throughout the tropics. They are of significant environmental and socio-economic importance in the tropics, especially in South Asia (China, Vietnam, India and Sri Lanka) and East Africa (Kenya, Tanzania and Egypt). Three international Casuarina workshops and many other meetings testify to the world, the significance of these plants, especially *Casuarina equisetifolia* L. (Pinyopusarerk *et al.*, 1996). India is the largest casuarina growing country in the world with an estimated 8, 00,000 ha of plantations particularly on the eastern coast (Pinyopusarerk *et al.*, 2000).

Casuarina equisetifolia L. is cultivated for a range of products and services that include pulpwood for paper making, poles for construction, fuel wood, windbreaks, shelterbelts and for afforesting mined areas. Being a nitrogen-fixing tree and amenable for growing in high density plantations under short durations of 3-4 years have made it an ideal tree for agroforestry systems (Viswanath *et al.*, 2001).

Indian researchers recommend the use of casuarina pulp for papermaking, although some long-fibered pulp such as bamboo is needed for blending in order to make paper on fast-running machines. Mysore Paper Mills, Karnataka, is expected to plant about 60 lakh clonal plants annually of hybrid *Casuarina sp.*, *Acacia sp.* and *Eucalyptus sp.* (Mandal *et al.*, 2007). *Casuarina equisetifolia* L. is one of the major species promoted by the Andhra Pradesh Paper Mills Ltd.

(Walker, 2006). Even though it is an important pulpwood species, literature describing the suitability of *Casuarina equisetifolia* for pulp and paper making is very limited. Verghese and Sivaramakrishna (1996) reported that the mean fibre diameters and fibre wall thickness were 4.0-10.8 µm and 2.1-3.3 µm respectively in 10-y-old *C. equisetifolia* trees grown in India. On the other hand, El-Osta *et al.* (1981) reported greater mean fibre diameter (13.8 µm) and fibre wall thickness (5.0 µm) in *C. equisetifolia* in Egypt.

MATERIALS AND METHODS

MATERIALS AND METHODS

3.1. MATERIAL

The present investigation was carried out to find the variation in wood anatomical properties of selected clones of Casuarina *equisetifolia* L. grown in Karur district, Tamil Nadu for pulp and paper making. The experimental material consists of wood samples collected from 42 clones of *Casuarina equisetifolia* L. from the provenance cum progeny testing trial of the Institute of Forest Genetics and Tree Breeding (IFGTB) at Coimbatore. The project was carried out in the department of Wood Science, College of Forestry, Kerala Agricultural University during 2011-2013.

3.1.1 Experimental site

The study material was collected from Karur district of Tamil Nadu through IFGTB. In order to widen the genetic base of clones used in farm forestry, IFGTB conducted clonal testing with a large collection of clones. The clones were selected from the genetic gain trial established at Puducherry in 2003 using the bulked seeds obtained from the first generation seedling seed orchard (SSO) at Sadivayal (Karunya campus), Coimbatore. A total of 87 clones and 3 seedlots were selected. The clones were selected based on individual tree superiority for height, diameter at breast height and straightness of stem through index selection method. These clones were tested in three locations namely (1) Mayiladumparai, near Kulithalai, Tamil Nadu (Inland, red soil), (2) Moorthypuram, near Karur, Tamil Nadu (Inland, sodic soil) and (3) Sirugramam, near Cuddalore, Tamil Nadu (Casuarina growing zone). The spacing adopted was 3m × 5m with 3 ramets per clone. A total of three 90 assertions were tested in these three locations. Forty six assertions tested in Karur district, were selected for the present study. The age of clones was 3 years. Karur district is located 11.00° N to 12.00° N and 77.28° E to 77.50° E and at an altitude of 122m above sea level. The highest temperature is obtained in early May to early June usually about 37 °C, though it usually exceeds

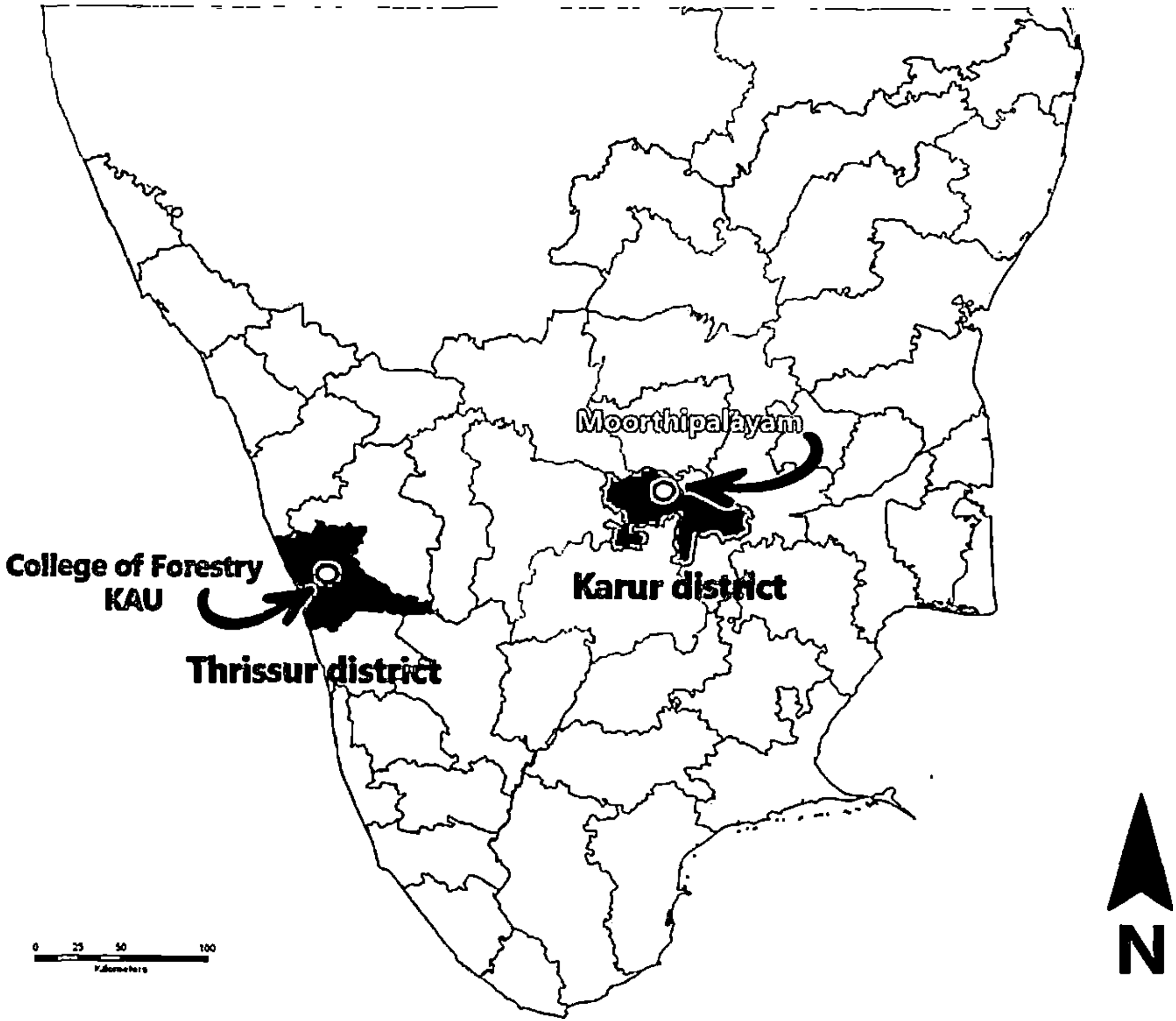

Fig.1. Map showing the study area

39 °C for a few days most years. Average daily temperature in Karur during January is around 24 °C, though the temperature rarely falls below 19 °C. The average annual rainfall is about 615 mm. The city gets most of its seasonal rainfall from the north-east monsoon winds, from late September to mid-November. Black soil is the predominant soil type in Karur district accounting for 35.51% followed by lateritic soil for 23.85%. The other type of soil is sandy, coastal alluvium for 20.31%.

3.2 METHODOLOGY

3.2.1 Selection of samples

Billets of length 1 meter were cut from the basal position of one tree (ramet) each selected randomly from the clones. The clones were raised from provenance cum progeny trial of the IFGTB. Three transverse discs (6 cm thick) collected from base, middle, and bottom positions of each of the billets.

3.2.3 Preparation of samples

The transverse discs collected from billets were further converted to smaller specimens for undertaking studies on wood physical, chemical and anatomical properties. For this discs were cut into two transverse halves. One half was used for estimation of wood specific gravity and the other half was used for studying anatomical properties and for cellulose and lignin estimation. Sampling methodology is given in plate 1.

3.2.3.1 Wood specific gravity

For specific gravity measurements five wood blocks of dimensions 2cm × 2cm × 2cm was taken from one half of the transverse discs. (plate 2A)

3.2.3.2 Wood anatomical properties

Small rectangular blocks (approximate size of 1cm × 1cm × 1cm) are taken from other half of the transverse disc.

3.2.3.3 Wood chemical properties

Wood blocks were also taken from the transverse discs for the estimation of 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 casuarina clones was determined using a specific gravity module attached to a precision electronic balance (Schimadzu AUY 220) (plate 2B). Specific gravity measurement was estimated on fresh, air dry and oven dry weight basis. To obtain fresh weight specific gravity, the samples were soaked in water for one day and then measured using the specific gravity module immediately after taking out from water. 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 appro imately constant temperature of 102   1 , for such a time as is needed to make its weight constant.

3.2.4.2 Anatomical properties

The anatomical features that were assessed include frequency, size and distribution of various cell types viz. vessels, rays and fibers.

3.2.4.2.1 Microtomy

Wood specimens of size less than 1 cm^3 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 (plate 9) of 10-15 µm thickness were prepared using a Leica sliding microtome (Leica SM 2000 R; plate 3A).

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 was 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 axial positions viz., base, middle and top. 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). For 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 (size 75mm x 25mm, thickness 1mm) and covered by cover slips.

3.2.4.2.4 Image Analysis

Microscopic examination and quantification of sections were undertaken using an Image Analyzer (Labomed-Digi 2; Plate 4). 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; plate 7). The software provides several classes of measurements like length, diameter, area and count.

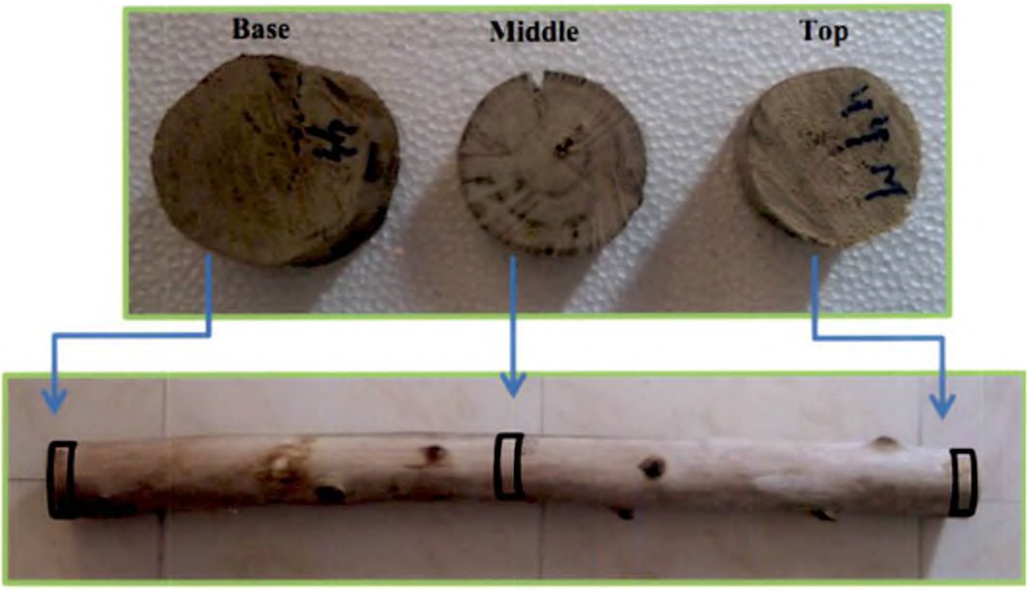

Plate 1. Discs taken from top, middle and base positions of the billet

Plate 2. (A) Rectangular blocks taken from discs for specific gravity analysis, (B) Specific gravity module attached to electronic balance (Schimadzu AUY 220)

Plate 3.Sliding microtome (leica SM 2000R) used for wood sectioning

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Plate 4. Image analyser (Labomed Digi-2) used for anatomical quantification

Plate 5.Powdered wood used for cellulose estimation

Plate 6.Spectrophotometer used for cellulose estimation

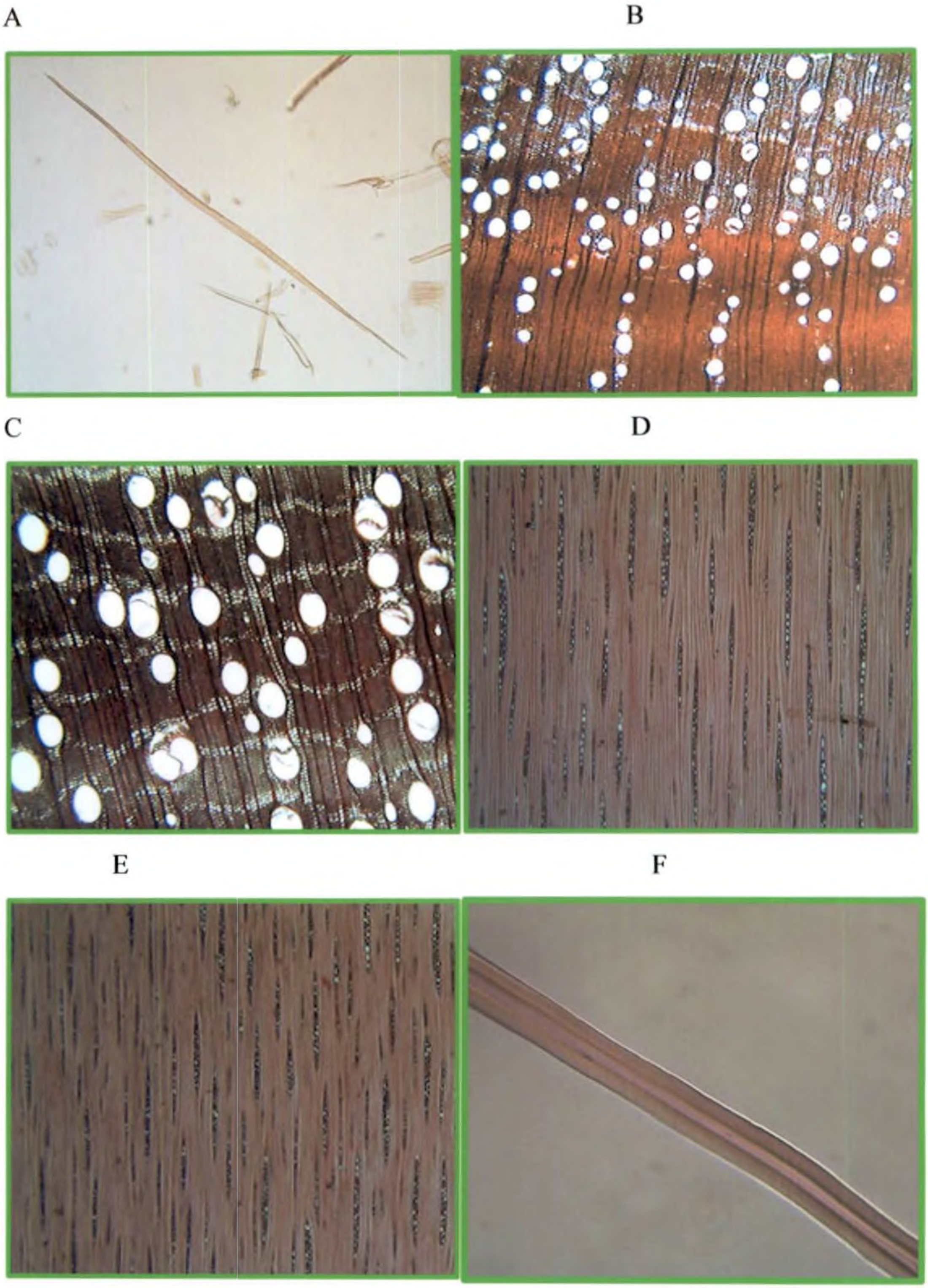


Plate 7. Photos taken using image analyser:(A) Fibre (10x) isolated by maceration, (B) Transverse section (10x) taken using sliding microtome, (C) Transverse section (40x) taken using sliding microtome, (D) Tangential section (40x) taken using sliding microtome (E) Tangential section (10x) taken using sliding microtome and (F) Fibre lumen and wall (40x) obtained by maceration

3.2.4.2.5 Observations

From the macerated fibres, observations like fibre length, fibre diameter (μm), fibre wall thickness (μm), fibre lumen diameter (μm) and vessel length (μm) for each clone were measured using the Image Analyzer. Each measurement was repeated five times for all the above characters at different height levels and is expressed in micrometers (μm). Tangential longitudinal sections (T.L.S) were used to measure ray height (μm), ray frequency and ray width (μm), whereas transverse sections (T.S) were used to determine vessel area (μm^2), vessel diameter (μm) and vessel frequency. Vessel and ray frequency (vessels/ray per mm^2) was determined by counting the number of vessels/rays 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). 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; Yanez-Espinosa *et al.*, 2004):

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

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

$$\text{Rigidity Coefficient} = \frac{2 \text{ x Fibre Wall Thickness (FWT)}}{\text{Fibre diameter (FD)}} \times 100$$

$$\text{Flexibility Coefficient} = \frac{2 \text{ x Fibre Lumen Diameter (FLD)}}{\text{Fibre diameter (FD)}} \times 100$$

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

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 (plate 5). 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; plate 6) 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,

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

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 extractive free xylem residue (EXR)

Soluble sugars, phenolics and extractives from the xylem powder were removed using a soxhlet apparatus (plate 8). One gram cell wall residue (CWR) was weighed in labeled 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 9.

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 are given in plate 8. 1-20 mg EXR was weighed in an eppendorf 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 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

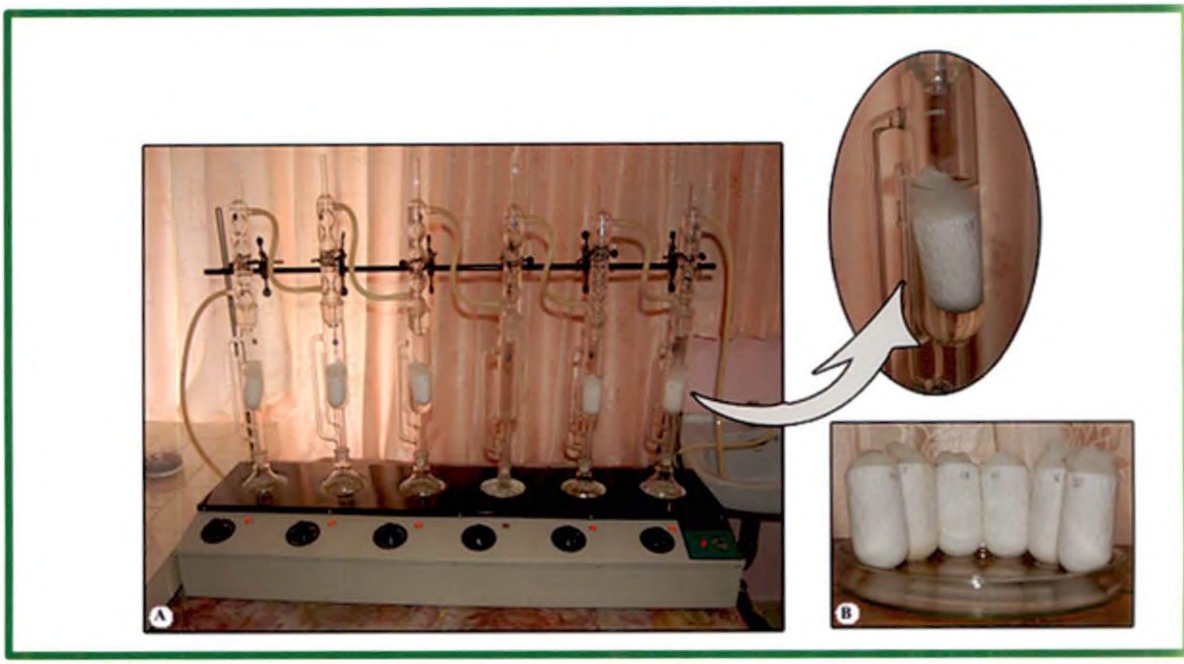


Plate 8.Purification of wood powder and preparation of EXR for estimation of lignin: (A) Soxhelt apparatus used for purification, (B) Extraction thimble (25 ×70 mm) bunged with cotton wool

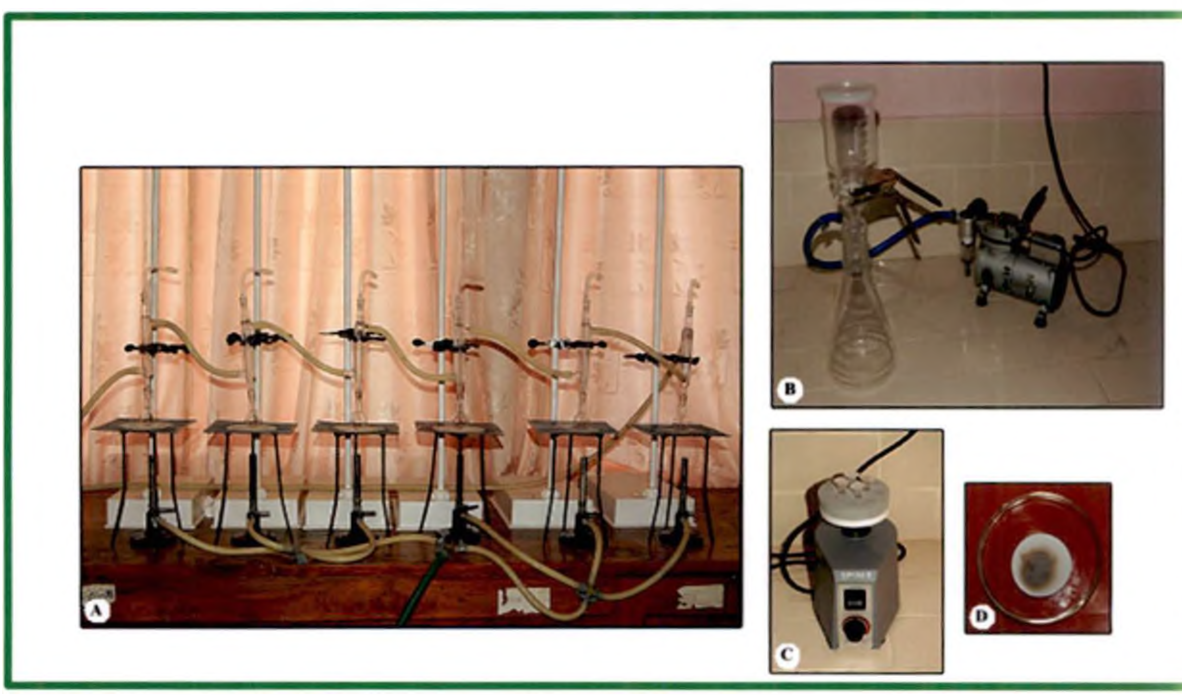


Plate 9.The microklason technique of quantification of insoluble lignin (A) Round bottomed flask assembly, (B) Vacuum filtration system, (C) Vortex mixer used for mixing, (D) Pre-weighed glass micrifibrewith lignin residue.

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); and 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 study was an attempt to study the variation in wood properties of 46 clones of *Casuarina equisetifolia* L. Three discs were collected from base, middle and top positions of billets of each clone for studying intra- and inter-clonal variation. Thus each sample (clone) is composed of sub sample (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 within and between clones, using the statistical package, MINITAB (ver. 16) and SPSS (ver. 17). 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 of clones. Simple correlation coefficient was computed taking complete set of data to examine the interrelationships between wood properties.

RESULT

RESULT

Results obtained by studying wood variation of 46 clones of *Casuarina equisetifolia* L. grown in Karur district of Tamil Nadu with special reference for their suitability for pulp and paper making are presented here under following categories,

I. Physical properties

A. Specific gravity

i. Fresh weight basis

ii. Air dry basis

iii. Oven dry basis

II. Anatomical properties

A. Fibre morphology

i. Fibre length

ii. Fibre diameter

iii. Fibre wall thickness

iv. Fibre lumen diameter

B. Ratios and factors

i. Runkel ratio

ii. Shape factor

iii. Slenderness ratio

iv. Coefficient of flexibility

v. Coefficient of rigidity

C. Ray morphology

i. Ray height

ii. Ray width

iii. Ray frequency

D. Vessel morphology

i. Vessel area

ii. Vessel diameter

iii. Vessel frequency

iv. Vessel length

III. Chemical properties

i. Cellulose content

ii. Lignin content

4.1 INTRA- AND INTER-CLONAL VARIATIONS IN WOOD PHYSICAL AND ANATOMICAL PROPERTIES

Nested ANOVA was used for statistical testing of intra and interclonal variation of wood physical and anatomical properties. ANOVA showed that all the physical and anatomical properties except fibre lumen width, runkel ratio, rigidity coefficient, flexibility coefficient and shape factor, showed significant difference between clones. Within clone variation was also significant for all the physical and anatomical parameters except oven dry specific gravity.

4.1.1 Physical Properties

4.1.1.1 Specific gravity

4.1.1.1a. Variation among clones

Results of the analysis of variance showed that specific gravity (air dry, fresh weight and oven dry basis) variation is significant among clones. The overall average specific gravity (air dry), specific gravity (fresh weight) and specific gravity (oven dry) of clones were 0.794, 1.161 and 0.741 respectively (table 1). Average whole tree specific gravity (air dry) ranges from 0.635 (clone 85) to 0.869 (clone 56), specific gravity (fresh weight) from 1.047 (clone 1) to 1.296

(clone 11) and specific gravity (oven dry) from 0.594 (for clone 85) to 0.830 (clone 69).

On the basis of specific gravity (air dry), all 46 clones were grouped together into 19 subsets (figure 2). The subsets described in increasing order. In subset 1 only one clone was there which had specific gravity (air dry) of 0.635 (clone 85). In the subset 2 specific gravity (air dry) ranged from 0.698 to 0.729 and clones were: (clone 62< clone 12< clone 53); in subset 3 it ranged from 0.726 to 0.761 and the clones were: (clone 12< clone 53< clone 20< clone 61< clone 89< clone 1< clone 30< clone 68< clone 90< clone 87< clone 74); in subset 4 it ranged from 0.736 to 0.771 and clones were: (clone 20< clone 61< clone 89< clone 1< clone 30< clone 68< clone 90< clone 87< clone 74< clone 35); in subset 5 it ranged from 0.739 to 0.776 and clones were: (clone 30< clone 68< clone 90< clone 87< clone 74< clone 35< clone 49< clone 54< clone 63< clone 44< clone 60); in subset 6 it ranged from 0.744 to 0.780 and clones were: (clone 89< clone 1< clone 30< clone 68< clone 90< clone 87< clone 74< clone 35< clone 49< clone 54< clone 63); in subset 7 it ranged from 0.751 to 0.787 and clones were: (clone 30< clone 68< clone 90< clone 87< clone 74< clone 35< clone 49< clone 54< clone 63< clone 44< clone 60); in subset 8 it ranged from 0.755 to 0.791 and clones were: (clone 90< clone 87< clone 74< clone 35< clone 49< clone 54< clone 63< clone 44< clone 60< clone 36< clone 59< clone 11< clone 46< clone 3); in subset 9 it ranged from 0.761 to 0.800 and clones were: (clone 74< clone 35< clone 49< clone 54< clone 63< clone 44< clone 60< clone 36< clone 59< clone 11< clone 46< clone 3< clone 88< clone 4< clone 86); in subset 10 it ranged from 0.771 to 0.804 and clones were: (clone 35< clone 49< clone 54< clone 63< clone 4< clone 60< clone 36< clone 59< clone 11< clone 46< clone 3< clone 88< clone 4< clone 86< clone 83< clone 45); in subset 11 it ranged from 0.776 to 0.814 and clones were: (clone 49< clone 54< clone 63< clone 44< clone 60< clone 36< clone 59< clone 11< clone 46< clone 3< clone 88< clone 4< clone 86< clone 83< clone 45< clone 58); in subset 12 it ranged from 0.787 to 0.823 and clones were: (clone 60< clone 36< clone 59< clone 11< clone 46< clone 3< clone 88< clone 4< clone 86< clone 83< clone 45< clone 58< clone 25); in subset 13 it ranged from 0.786 to 0.828 and clones were: (clone 36< clone 59< clone 11< clone 46< clone 3< clone 88< clone 4< clone 86< clone 83< clone 45< clone 58< clone 25< clone 29); in subset 14 it ranged from 0.798 to 0.832 and clones were: (clone 88< clone 4< clone 86< clone 83< clone 45< clone 58< clone 25< clone 29< clone 5); in subset 15 it ranged from 0.804 to 0.840 and clones were: (clone 45< clone 58< clone 25< clone 29< clone 5< clone 72); in subset 16 it ranged from 0.814 to 0.852 and clones were: (clone 58< clone 25< clone 29< clone 5< clone 72< clone 84< clone 47< clone 55< clone 31< clone 48< clone 51< clone 73< clone 64); in subset 17 it ranged from 0.823 to 0.861 and clones were: (clone 25< clone 29< clone 5< clone 72< clone 84< clone 47< clone 55< clone 31< clone 48< clone 51< clone 73< clone 64< clone 66); in subset 18 it ranged from 0.828 to 0.864 and clones were: (clone 29< clone 5< clone 72< clone 84< clone 47< clone 55< clone 31< clone 48< clone 51< clone 73< clone 64< clone 66< clone 33); in subset 19 it ranged from 0.831 to 0.869 and clones were: clone 5< clone 72< clone 84< clone 47< clone 55< clone 31< clone 48< clone 51< clone 73< clone 64< clone 66< clone 33< clone 69< clone 56).

On the basis of specific gravity (fresh weight) all 46 clones were divided into 18 different subsets (figure 2). Specific gravity (fresh weight) in subset I ranged from 1.047 to 1.088 and clones were (clone 1< clone 89< clone 54< clone 90< clone 63< clone 60); In the subset 2 specific gravity (fresh weight) ranged from 1.068 to 1.100 and clones were: (clone 54< clone 90< clone 63< clone 60< clone 20< clone 30< clone 33<); in subset 3 it ranged from 1.077 to 1.120 and the clones were: (clone 90< clone 63< clone 60< clone 20< clone 30< clone 33< clone 87< clone 51<); in subset 4 it ranged from 1.084 to 1.130 and clones were: (clone 63< clone 60< clone 20< clone 30< clone 33< clone 87< clone 51< clone 47<); in subset 5 it ranged from 1.088 to 1.133 and clones were: (clone 60< clone 20< clone 30< clone 33< clone 87< clone 51< clone 47< clone 44<); in subset 6 it ranged from 1.097 to 1.140 and clones were: (clone 20< clone 30< clone 33< clone 87< clone 51< clone 47< clone 44< clone 49<); in subset 7 it ranged from 1.010 to 1.146 and clones were: (clone 30< clone 33< clone 87< clone 51< clone 47< clone 44< clone 49< clone 4<); in subset 8 it ranged from 1.118 to 1.166 and clones were: (clone 87< clone 51< clone 47< clone 44< clone 49< clone 4< clone 74< clone 73< clone 59< clone 68< clone 55< clone 5< clone 58<); in subset 9 it ranged from 1.120 to 1.168 and clones were: (clone 51< clone 47< clone 44< clone 49< clone 4< clone 74<clone 73<clone 59< clone 68< clone 55< clone 5< clone 58< clone 56< clone 46<); in subset 10 it ranged from 1.129 to 1.177 and clones were: (clone 47< clone 44< clone 49< clone 4< clone 74< clone 73< clone 59< clone 68< clone 55< clone 5< clone 58< clone 56< clone 46< clone 29< clone 53< clone 88<); in subset 11 it ranged from 1.133 to 1.182 and clones were: (clone 44< clone 49< clone 4< clone 74< clone 73< clone 59< clone 68< clone 55< clone 5< clone 58< clone 56< clone 46< clone 29< clone 53< clone 88< clone 85< clone 45<); in subset 12 it ranged from 1.140 to 1.187 and clones were: (clone 49< clone 4< clone 74< clone 73< clone 59< clone 68< clone 55< clone 5< clone 58< clone 56< clone 46< clone 29< clone 53< clone 88< clone 85< clone 45< clone 12< clone 61< clone 72<); in subset 13 it ranged from 1.146 to 1.192 and clones were: (clone 4< clone 74< clone 73< clone 59< clone 68< clone 55< clone 5< clone 58< clone 56< clone 46< clone 29< clone 53< clone 88< clone 85< clone 45< clone 12< clone 61< clone 72< clone 83< clone 3<); in subset 14 it ranged from 1.154 to 1.203 and clones were: (clone 73< clone 59< clone 68< clone 55< clone 5< clone 58< clone 56< clone 46< clone 29< clone 53< clone 88< clone 85< clone 45< clone 12< clone 61< clone 72< clone 83< clone 3< clone 64<); in subset 15 it ranged from 1.161 to 1.211 and clones were: (clone 55< clone 5< clone 58< clone 56< clone 46< clone 29< clone 53< clone 88< clone 85< clone 45< clone 12< clone 61< clone 72< clone 83< clone 3< clone 64< clone 25< clone 35< clone 86< clone 36< clone 69< clone 62); in subset 16 it ranged from 1.166 to 1.212 and clones were: (clone 58< clone 56< clone 46< clone 29< clone 53< clone 88< clone 85< clone 45< clone 12< clone 61< clone 72< clone 83< clone 3< clone 64< clone 25< clone 35< clone 86< clone 36< clone 69< clone 62< clone 31); in subset 17 it ranged from 1.174 to 1.229 and clones were: (clone 29< clone 53< clone 88< clone 85< clone 45< clone 12< clone 61< clone 72< clone 83< clone 3< clone 64< clone 25< clone 35< clone 86< clone 36< clone 69< clone 62< clone 31< clone 48< clone 84); in subset 18 it ranged from 1.192 to 1.240 and clones were (clone 3< clone 64< clone 25< clone 35< clone 86< clone 36< clone 69< clone 62< clone 31< clone 48< clone 84< clone 66< Clone 11).

On the basis of specific gravity (oven dry) all 46 clones were divided into 18 different subsets (figure 2). Subset 1 had only one clone (clone 85) and the specific gravity value was 0.5986 ; In the subset 2 specific gravity (oven dry) ranged from 0.6685 to 0.7092 and clones were: (clone 62< clone 89< clone 12< clone 1< clone 90< clone 53< clone 20< clone 61); in subset 3 it ranged from 0.6805 to 0.7251 and the clones were: (clone 89< clone 12< clone 1< clone 90< clone 53< clone 20< clone 61< clone 63< clone 68< clone 36< clone 86); in subset 4 it ranged from 0.6882 to 0.7331 and clones were: (clone 12< clone 1< clone 90< clone 53< clone 20< clone 61< clone 63<clone 68< clone 36< clone 86< clone 30< clone 11< clone 54< clone 87< clone 49< clone 74); in subset 5 it ranged from 0.6909 to 0.7359 and clones were: (clone 1< clone 90< clone 53< clone 20< clone 61< clone 63< clone 68< clone 36< clone 86< clone 30< clone 11< clone 54< clone 87< clone 49< clone 74< clone 44); in subset 6 it ranged from 0.6952 to 0.7381 and clones were: (clone 53< clone 20< clone 61< clone 63< clone 68< clone 36< clone 86< clone 30< clone 11< clone 54< clone 87< clone 49< clone 74< clone 44< clone 88< clone 35); in subset 7 it ranged from 0.6982 to 0.7445 and clones were: (clone 20< clone 61< clone 63< clone 68<clone 36<clone 86<clone 30<clone 11< clone 54< clone 87< clone 49< clone 74< clone 44< clone 88< clone 35< clone 4< clone 59< clone 47< clone 46); in subset 8 it ranged from 0.7092 to 0.7539 and clones were: (clone 61< clone 63< clone 68< clone 36< clone 86< clone 30< clone 11< clone 54< clone 87< clone 49< clone 74< clone 44< clone 88< clone 35< clone 4< clone 59< clone 47< clone 46< clone 3< clone 48< clone 29< clone 83< clone 25); in subset 9 it ranged from 0.7135 to 0.7593 and clones were: (clone 63< clone 68< clone 36< clone 86< clone 30< clone 11< clone 54< clone 87< clone 49< clone 74< clone 44< clone 88< clone 35< clone 4< clone 59< clone 47< clone 46< clone 3< clone 48< clone 29< clone 83< clone 25< clone 33< clone 84); in subset 10 it ranged from 0.7230 to 0.7658 and clones were: (clone 36< clone 86< clone 30< clone 11<

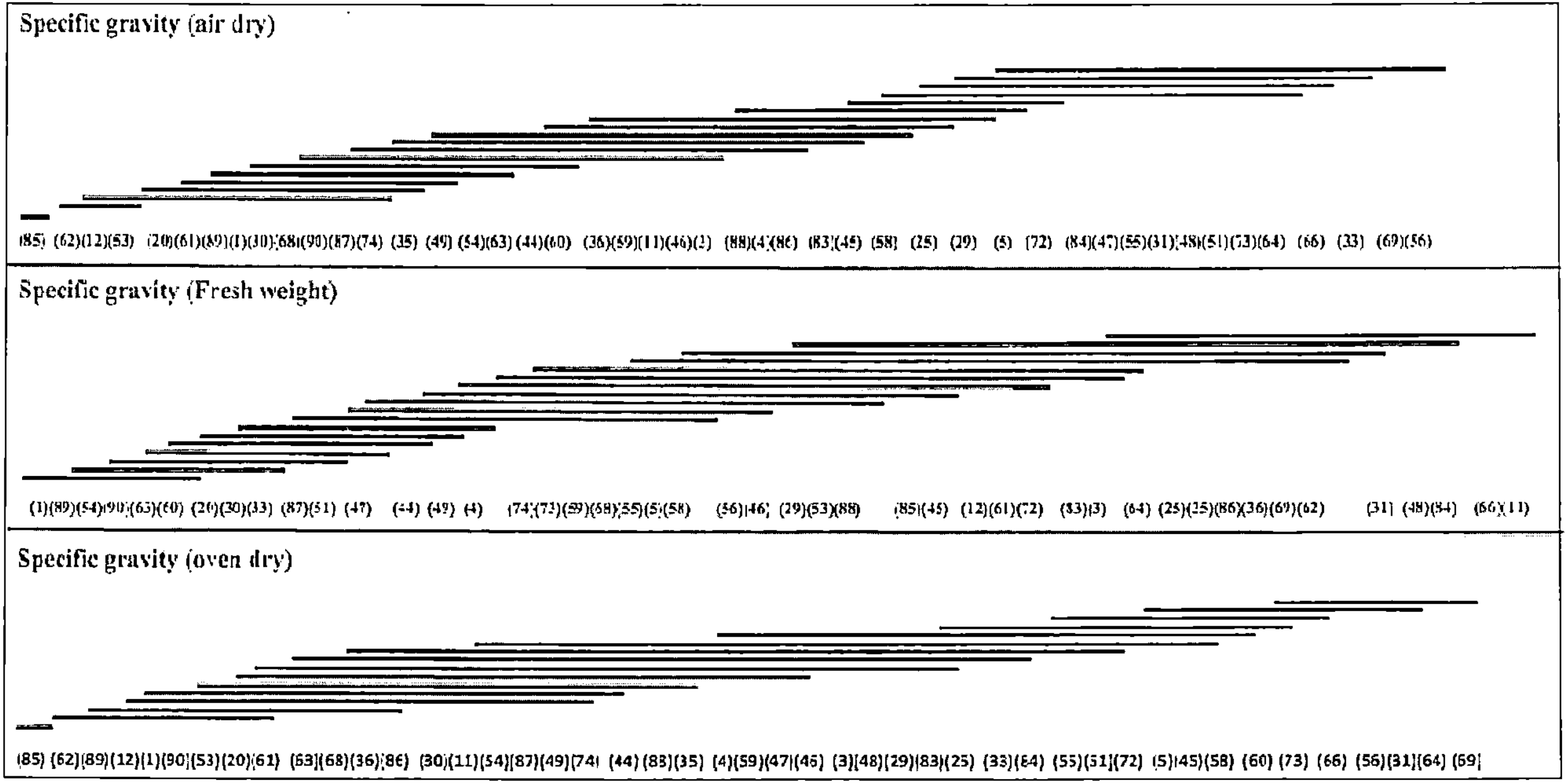


Fig.2. Bar diagram of all 47 trees on the basis of wood specific gravity.

clone 54< clone 87< clone 49< clone 74< clone 44< clone 88< clone 35< clone 4< clone 59< clone 47< clone 46< clone 3< clone 48< clone 29< clone 83< clone 25< clone 33< clone 84< clone 55< clone 51< clone 72); in subset 11 it ranged from 0.7302 to 0.7762 and clones were: (clone 54< clone 87< clone 49< clone 74< clone 44< clone 88< clone 35< clone 4< clone 59< clone 47< clone 46< clone 3< clone 48< clone 29< clone 83< clone 25< clone 33< clone 84< clone 55< clone 51< clone 72< clone 5< clone 45< clone 58); in subset 12 it ranged from 0.7419 to 0.7865 and clones were: (clone 4< clone 59< clone 47< clone 46< clone 3< clone 48< clone 29< clone 83< clone 25< clone 33< clone 84< clone 55< clone 51< clone 72< clone 5< clone 45< clone 58< clone 60); in subset 13 it ranged from 0.7539 to 0.7983 and clones were: (clone 25< clone 33< clone 84< clone 55< clone 51< clone 72< clone 5< clone 45< clone 58< clone 60< clone 73); in subset 14 it ranged from 0.7631 to 0.8056 and clones were: (clone 55< clone 51< clone 72< clone 5< clone 45< clone 58< clone 60< clone 73< clone 66); in subset 15 it ranged from 0.7754 to 0.8137 and clones were: (clone 5< clone 45< clone 58< clone 60< clone 73< clone 66< clone 56< clone 31< clone 64); in subset 16 it ranged from 0.7983 to 0.8330 and clones were: (clone 73< clone 66< clone 69).

Table 1: Mean specific gravity (air, fresh weight and oven dry) of the different clones.

Clone number	Specific gravity (air dry)	Specific gravity (fresh weight)	Specific gravity (oven dry)
Clone 1	0.74 (0.011)	1.05 (0.011)	0.69 (0.011)
Clone 3	0.79 (0.009)	1.19 (0.007)	0.75 (0.014)
Clone 4	0.8 (0.016)	1.15 (0.006)	0.74 (0.013)
Clone 5	0.83 (0.008)	1.16 (0.007)	0.78 (0.008)
Clone 11	0.79 (0.019)	1.30 (0.06)	0.73 (0.02)
Clone 12	0.73 (0.01)	1.19 (0.002)	0.69 (0.018)
Clone 20	0.74 (0.012)	1.10 (0.005)	0.70 (0.012)

Clone 25	0.82 (0.012)	1.21 (0.012)	0.75 (0.029)
Clone 29	0.83 (0.016)	1.17 (0.007)	0.75 (0.015)
Clone 30	0.75 (0.007)	1.10 (0.006)	0.73 (0.009)
Clone 31	0.84 (0.008)	1.21 (0.015)	0.81 (0.008)
Clone 33	0.86 (0.008)	1.10 (0.004)	0.76 (0.007)
Clone 35	0.77 (0.008)	1.21 (0.004)	0.74 (0.009)
Clone 41	0.79 (0.025)	1.21 (0.006)	0.72 (0.017)
Clone 44	0.78 (0.011)	1.13 (0.009)	0.74 (0.011)
Clone 45	0.8 (0.018)	1.18 (0.009)	0.78 (0.009)
Clone 46	0.79 (0.01)	1.17 (0.007)	0.74 (0.009)
Clone 47	0.84 (0.014)	1.13 (0.006)	0.74 (0.018)
Clone 48	0.85 (0.026)	1.22 (0.008)	0.75 (0.01)
Clone 49	0.78 (0.011)	1.14 (0.03)	0.73 (0.01)
Clone 51	0.85 (0.011)	1.12 (0.009)	0.77 (0.013)
Clone 53	0.73 (0.008)	1.18 (0.012)	0.70 (0.01)
Clone 54	0.78 (0.008)	1.07 (0.005)	0.73 (0.008)
Clone 55	0.84 (0.015)	1.16 (0.008)	0.76 (0.01)
Clone 56	0.87 (0.008)	1.17 (0.005)	0.81 (0.01)
Clone 58	0.81 (0.012)	1.17 (0.006)	0.78 (0.008)
Clone 59	0.79 (0.01)	1.15 (0.012)	0.74 (0.012)
Clone 60	0.79 (0.006)	1.09 (0.007)	0.79 (0.008)
Clone 61	0.74 (0.012)	1.19 (0.004)	0.71 (0.014)
Clone 62	0.70 (0.011)	1.21 (0.041)	0.67 (0.012)
Clone 63	0.78 (0.008)	1.08 (0.005)	0.71 (0.012)

Clone 64	0.85 (0.013)	1.20 (0.008)	0.81 (0.011)
Clone 66	0.86 (0.005)	1.24 (0.045)	0.81 (0.013)
Clone 68	0.75 (0.015)	1.16 (0.007)	0.72 (0.015)
Clone 69	0.87 (0.01)	1.21 (0.007)	0.83 (0.011)
Clone 72	0.84 (0.009)	1.19 (0.005)	0.77 (0.011)
Clone 73	0.85 (0.006)	1.15 (0.006)	0.80 (0.006)
Clone 74	0.76 (0.009)	1.15 (0.006)	0.73 (0.011)
Clone 83	0.80 (0.012)	1.19 (0.005)	0.75 (0.019)
Clone 84	0.84 (0.016)	1.22 (0.005)	0.76 (0.032)
Clone 85	0.63 (0.013)	1.18 (0.008)	0.59 (0.02)
Clone 86	0.80 (0.01)	1.21 (0.003)	0.73 (0.014)
Clone 87	0.76 (0.011)	1.12 (0.008)	0.73 (0.011)
Clone 88	0.80 (0.012)	1.18 (0.008)	0.74 (0.014)
Clone 89	0.74 (0.007)	1.05 (0.006)	0.68 (0.005)
Clone 90	0.75 (0.011)	1.08 (0.009)	0.69 (0.012)
Total	**0.79 (0.003)**	**1.161 (0.003)**	**0.741 (0.003)**

(Value in parenthesis is standard error of mean)

4.1.1.1b. Within clone variation

Position wise pooled specific gravity variation of all clones was analysed. Average specific gravity (air dry) for different heights ranged from 0.799 (base) to 0.789 (middle); specific gravity (fresh weight) from 1.15 (middle) to 1.17 (base); specific gravity (oven dry) from 0.74 (middle) to 0.75 (base). In general, the different wood specific gravity values (air, fresh weight and oven dry) were decreasing from base to middle and afterwards increasing from middle to top position (figure 3).

Fig.A

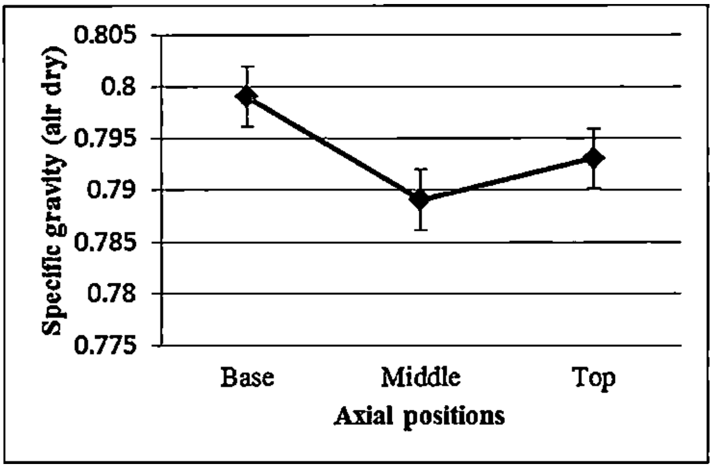


Fig. B

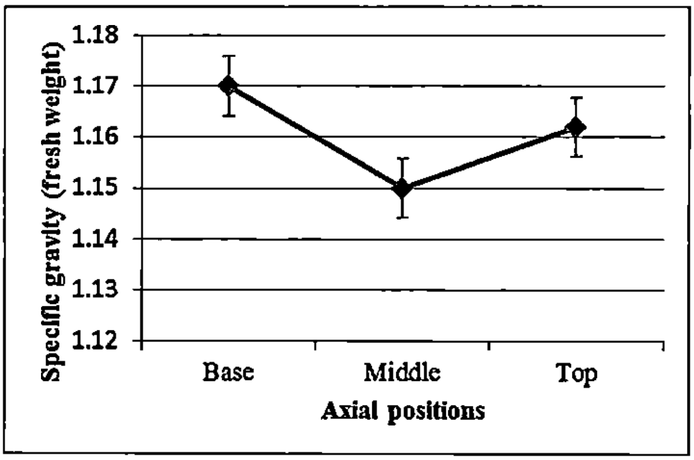


Fig. C

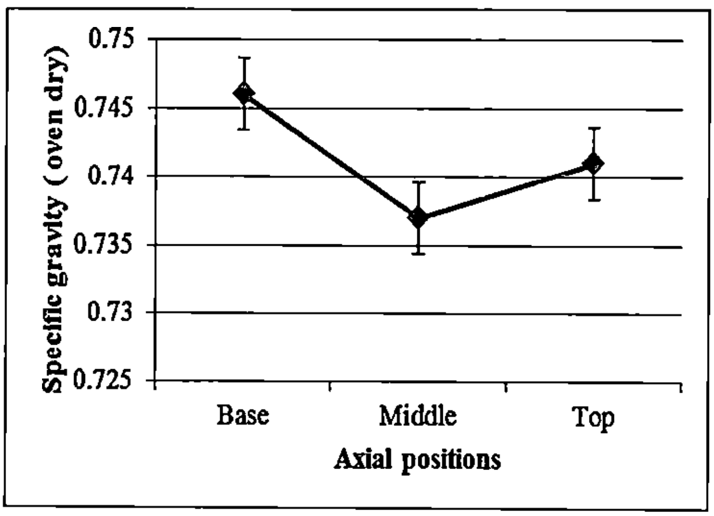


Fig.3. Axial variation in specific gravity (air dry, fresh weight and oven dry) of clones at three conditions

Table 2: Mean specific gravity (air dry, fresh and oven dry) at different heights of all the clones pooled together.

Positions	Specific gravity (air dry)	Specific gravity (fresh weight)	Specific gravity (oven dry)
Base	0.799 (0.004)	1.170 (0.006)	0.746 (0.004)
Middle	0.789 (0.005)	1.150 (0.005)	0.737 (0.005)
Top	0.793 (0.004)	1.162 (0.004)	0.741 (0.004)
Mean	**0.794 (0.003)**	**1.160 (0.003)**	**0.741 (0.003)**

(Value in parenthesis is standard error of mean)

4.1.2 Anatomical properties

4.1.2.1 Fibre morphology

4.1.2.1a. Variation among clones

Fibre parameters like fibre length, fibre width and fibre cell wall thickness showed significant variation among 46 clones. Table 3 shows pooled mean values fibre parameters of 46 clones. Average whole clone fibre length (μm) for different clones ranges from 1225.60 (clone 45) to 1726.49 (clone 4); fibre diameter (μm) from 20.690 (clone 90) to 29.608 (clone 61); fibre lumen width (μm) from 6.538 (69) to 12.526 (clone 45); fibre cell wall thickness (μm) from 5.731 (clone 4) to 9.336 (clone 56).

On the basis of fibre length all 46 clones were divided into 13 different subsets (figure 4). In the subset 1 fibre length ranged from 1225.60 to 1360.48 μm and clones were: (clone 45< clone 62< clone 90< clone 73< clone 58< clone 3< clone 36); in subset 2 it ranged from 1304.87 to 1457.65 μm and the clones were: (clone 62< clone 90< clone 73< clone 58< clone 3< clone 36< clone 11< clone 31< clone 20< clone 54< clone 12< clone 29< clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 5< clone 83< clone 60< clone 49< clone 35< clone 5); in subset 3 it ranged from 1325.01 to 1474.45 μm and clones were: (clone 73< clone 58< clone 3< clone 36< clone 11< clone 31< clone 20< clone

Fig.A

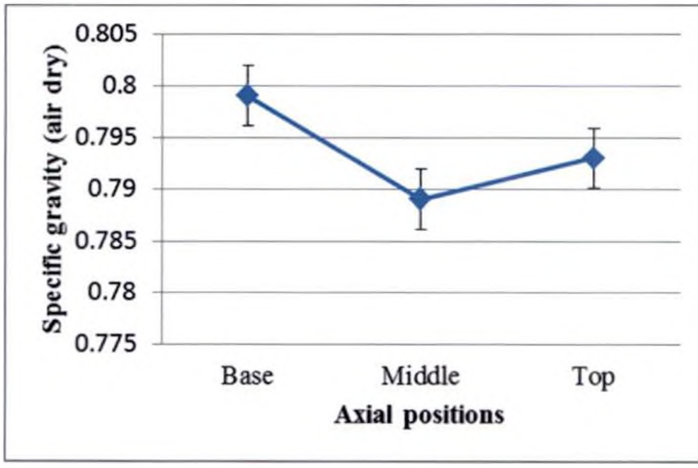


Fig. B

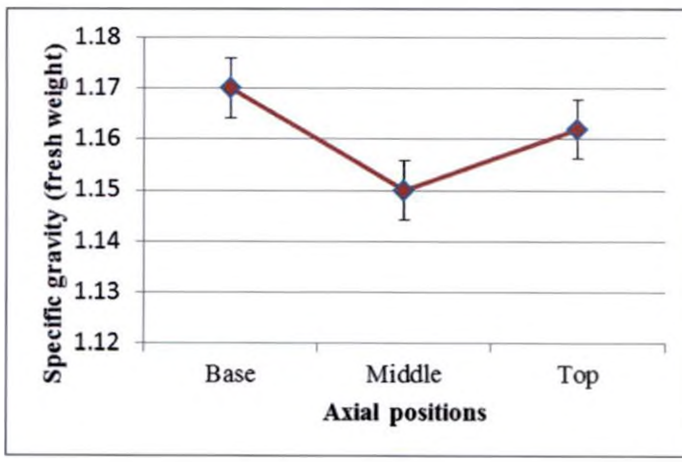
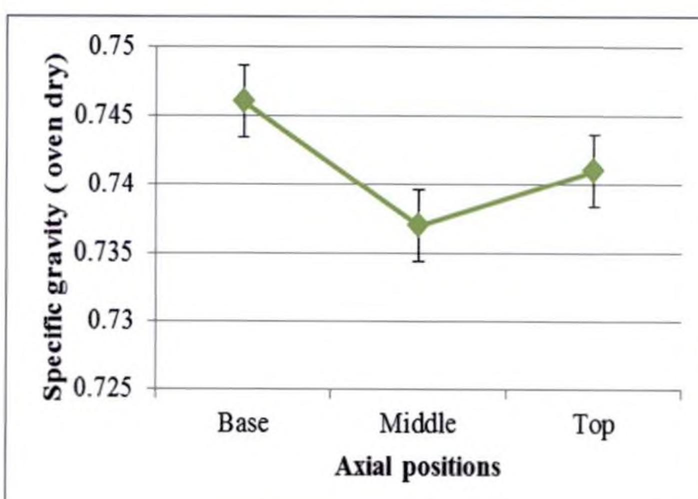


Fig. C



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Positions	Specific gravity (air dry)	Specific gravity (fresh weight)	Specific gravity (oven dry)
Base	0.799 (0.004)	1.170 (0.006)	0.746 (0.004)
Middle	0.789 (0.005)	1.150 (0.005)	0.737 (0.005)
Top	0.793 (0.004)	1.162 (0.004)	0.741 (0.004)
Mean	**0.794** **(0.003)**	**1.160** **(0.003)**	**0.741** **(0.003)**

(Value in parenthesis is standard error of mean)

4.1.2 Anatomical properties

4.1.2.1 Fibre morphology

4.1.2.1a. Variation among clones

Fibre parameters like fibre length, fibre width and fibre cell wall thickness showed significant variation among 46 clones. Table 3 shows pooled mean values fibre parameters of 46 clones. Average whole clone fibre length (µm) for different clones ranges from 1225.60 (clone 45) to 1726.49 (clone 4); fibre diameter (µm) from 20.690 (clone 90) to 29.608 (clone 61); fibre lumen width (µm) from 6.538 (69) to 12.526 (clone 45); fibre cell wall thickness (µm) from 5.731 (clone 4) to 9.336 (clone 56).

On the basis of fibre length all 46 clones were divided into 13 different subsets (figure 4). In the subset 1 fibre length ranged from 1225.60 to 1360.48 µm and clones were: (clone 45< clone 62< clone 90< clone 73< clone 58< clone 3< clone 36); in subset 2 it ranged from 1304.87 to 1457.65 µm and the clones were: (clone 62< clone 90< clone 73< clone 58< clone 3< clone 36< clone 11< clone 31< clone 20< clone 54< clone 12< clone 29< clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 5< clone 83< clone 60< clone 49< clone 35< clone 5); in subset 3 it ranged from 1325.01 to 1474.45 µm and clones were: (clone 73< clone 58< clone 3< clone 36< clone 11< clone 31< clone 20< clone

54< clone 12< clone 29< clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 5< clone 83< clone 60< clone 49< clone 35< clone 5< clone 33< clone 53< clone 64< clone 51< clone 86< clone 1); in subset 4 it ranged from 1342.20 to 1484.00 μm and clones were: (clone 58< clone 3< clone 36< clone 11< clone 31< clone 20< clone 54< clone 12< clone 29< clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 85< clone 83< clone 60< clone 49< clone 35< clone 5< clone 33< clone 53< clone 64< clone 51< clone 86< clone 1< clone 47< clone 88<); in subset 5 it ranged from 1348.83 to 1502.48 μm and clones were: (clone 3< clone 36< clone 11< clone 31< clone 20< clone 54< clone 12< clone 29< clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 85< clone 83< clone 60< clone 49< clone 35< clone 5<clone 33< clone 53< clone 64< clone 51< clone 86< clone 1< clone 47<clone 88<clone 30<clone 84); in subset 6 it ranged from 1360.48 to 1512.25 μm and clones were: (clone 36< clone 11< clone 31< clone 20< clone 54< clone 12< clone 29< clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 85< clone 83< clone 60< clone 49< clone 35< clone 5< clone 33< clone 53< clone 64< clone 51< clone 86< clone 1< clone 47< clone 88< clone 30<clone 84<clone 63<clone 48<clone 69<); in subset 7 it ranged from 1372.55 to 1527.27 μm and clones were: (clone 11< clone 31< clone 20< clone 54< clone 12< clone 29< clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 85< clone 83< clone 60< clone 49< clone 35< clone 5< clone 33< clone 53< clone 64< clone 51< clone 86< clone 1< clone 47< clone 88< clone 30< clone 84< clone 63< clone 48< clone 69< clone 25); in subset 8 it ranged from 1397.07 to 1549.40 μm and clones were: (clone 89< clone 68< clone 59< clone 44< clone 46< clone 87< clone 85< clone 83< clone 60< clone 49< clone 35< clone 5< clone 33< clone 53< clone 64< clone 51< clone 86< clone 1< clone 47< clone 88< clone 30< clone 84< clone 63< clone 48< clone 69< clone 25< clone 55); in subset 9 it ranged from 1421.42 to 1572.47 μm and clones were: (clone 46< clone 87< clone 85< clone 83< clone 60< clone 49< clone 35< clone 5<clone 33< clone 53< clone 64< clone 51< clone 86< clone 1< clone 47< clone 88< clone 30< clone 84< clone 63< clone 48< clone 69< clone 25< clone 55<clone 72); in subset 10 it

ranged from 1449.83 to 1598.80 μm and clones were: (clone 49< clone 35< clone 5<clone 33< clone 53< clone 64< clone 51< clone 86< clone 1< clone 47< clone 88< clone 30< clone 84< clone 63< clone 48< clone 69< clone 25< clone 55<clone 72< clone 56); in subset 11 it ranged from 1484.0 to 1629.12 μm and clones were: (clone 47< clone 88< clone 30< clone 84< clone 63< clone 48< clone 69< clone 25< clone 55<clone 72< clone 56< clone 61< clone 66); in subset 12 it ranged from 1500.57 to 1636.90 μm and clones were: (clone 30< clone 84< clone 63< clone 48< clone 69< clone 25< clone 55<clone 72< clone 56< clone 61< clone 66< clone 74); in subset 13 it ranged from 1598.80 to 1726.49 μm and clones were: (clone 56< clone 61< clone 66< clone 74< clone 4).

On the basis of fiber diameter all 46 clones were divided into 15 different subsets (figure 4). In the subset 1 fibre diameter ranged from 20.69 to 23.61 μm and clones were: (clone 90< clone 72< clone 29< clone 4< clone 3< clone 11< clone 73< clone 68< clone 62< clone 89); in subset 2 it ranged from 21.33 to 24.30 μm and the clones were: (clone 72< clone 29< clone 4< clone 3< clone 11< clone 73< clone 68< clone 62< clone 89< clone 5< clone 69< clone 33< clone 30); in subset 3 it ranged from 21.66 to 24.74 μm and clones were: (clone 29< clone 4< clone 3< clone 11< clone 73< clone 68< clone 62< clone 89< clone 5< clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20); in subset 4 it ranged from 22.16 to 25.26 μm and clones were: (clone 4< clone 3< clone 11< clone 73< clone 68< clone 62< clone 89< clone 5< clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85); in subset 5 it ranged from 22.71 to 25.79 μm and clones were: (clone 3< clone 11< clone 73< clone 68< clone 62< clone 89< clone 5< clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87); in subset 6 it ranged from 22.94 to 26.13 μm and clones were: (clone 11< clone 73< clone 68< clone 62< clone 89< clone 5< clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone

54); in subset 7 it ranged from 23.56 to 26.62 μm and clones were: (clone 68< clone 62< clone 89< clone 5< clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone 54< clone 45< clone 83< clone 64< clone 47); in subset 8 it ranged from 23.61 to 26.79 μm and clones were: (clone 89< clone 5< clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone 54< clone 45< clone 83< clone 64< clone 47< clone 55); in subset 9 it ranged from 24.00 to 27.15 μm and clones were: (clone 5< clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone 54< clone 45< clone 83< clone 64< clone 47< clone 55< clone 44); in subset 10 it ranged from 24.08 to 27.21 μm and clones were: (clone 69< clone 33< clone 30< clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone 54< clone 45< clone 83< clone 64< clone 47< clone 55< clone 44< clone 56); in subset 11 it ranged from 24.40 to 27.58 μm and clones were: (clone 46< clone 88< clone 31< clone 86< clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone 54< clone 45< clone 83< clone 64< clone 47< clone 55< clone 44< clone 56< clone 25 < clone 36); in subset 12 it ranged from 24.74 to 27.75 μm and clones were: (clone 20< clone 35< clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone 54< clone 45< clone 83< clone 64< clone 47< clone 55< clone 44< clone 56< clone 25 < clone 36< clone 63); in subset 13 it ranged from 25.09 to 28.23 μm and clones were: (clone 84< clone 49< clone 85< clone 74< clone 1< clone 59< clone 53< clone 58< clone 87< clone 60< clone 51< clone 48< clone 54< clone 45< clone 83< clone 64< clone 47< clone 55< clone 44< clone 56< clone 25 <

clone 36< clone 63< clone 12); in subset 14 it ranged from 26.13 to 29.05 µm and clones were: (clone 54< clone 45< clone 83< clone 64< clone 47< clone 55< clone 44< clone 56< clone 25 < clone 36< clone 63< clone 12< clone 66); in subset 15 it ranged from 26.79 to29.61 µm and clones were: (clone 55< clone 44< clone 56< clone 25 < clone 36< clone 63< clone 12< clone 66< clone 61).

On the basis of fiber lumen width all 46 clones were divided into 14 different subsets (figure 5). In the subset 1 fibre lumen width ranged from 6.57 to 9.34 µm and clones were: (clone 69< clone 90< clone 5< clone 46< clone 72< clone 89< clone 73< clone 62< clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54); in subset 2 it ranged from 7.05 to 9.89 µm and the clones were: (clone 90< clone 5< clone 46< clone 72< clone 89< clone 73< clone 62< clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1); in subset 3 it ranged from 7.11 to 9.92 µm and clones were: (clone 5< clone 46< clone 72< clone 89< clone 73< clone 62< clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83); in subset 4 it ranged from 7.19 to 9.99 µm and clones were: (clone 46< clone 72< clone 89< clone 73< clone 62< clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51); in subset 5 it ranged from 7.47 to 10.26 µm and clones were: (clone 72< clone 89< clone 73< clone 62< clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30); in subset 6 it ranged from 7.69 to 10.46 µm and clones were: (clone 89< clone 73< clone 62< clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44); in subset 7 it ranged from 7.88 to 11.74

μm and clones were: (clone 62< clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58); in subset 8 it ranged from 8.30 to 11.08 μm and clones were: (clone 3< clone 56< clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58< clone 87); in subset 9 it ranged from 8.55 to 11.36 μm and clones were: (clone 85< clone 4< clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58< clone 87< clone 60< clone 66< clone 36< clone 47); in subset 10 it ranged from 8.75 to 11.61 μm and clones were: (clone 31< clone 68< clone 29< clone 86< clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58< clone 87< clone 60< clone 66< clone 36< clone 47< clone 61); in subset 11 it ranged from 9.13 to 11.97 μm and clones were: (clone 84< clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58< clone 87< clone 60< clone 66< clone 36< clone 47< clone 61 < clone 12); in subset 12 it ranged from 9.28 to 12.09 μm and clones were: (clone 11< clone 54< clone 33< clone 20< clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58< clone 87< clone 60< clone 66< clone 36< clone 47< clone 61 < clone 12, clone 74); in subset 13 it ranged from 9.54 to 12.32 μm and clones were: (clone 25< clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58< clone 87< clone 60< clone 66< clone 36< clone 47< clone 61 < clone 12, clone 74< clone

63); in subset 14 it ranged from 9.69 to 12.53 μm and clones were: (clone 49< clone 64< clone 1< clone 83< clone 51< clone 35< clone 55< clone 48< clone 53< clone 30< clone 59< clone 88< clone 44< clone 58< clone 87< clone 60< clone 66< clone 36< clone 47< clone 61 < clone 12, clone 74< clone 63< clone 45).

On the basis of fiber cell wall thickness all 46 clones were divided into 10 different subsets (figure 5). In the subset 1 fibre cell wall thickness ranged from 5.73 to 7.04 μm and clones were: (clone 4< clone 29< clone 72< clone 74< clone 45< clone 11< clone 90< clone 30); in subset 2 it ranged from 5.99 to 7.33 μm and the clones were: (clone 29< clone 72< clone 74< clone 45< clone 11< clone 90< clone 30< clone 73< clone 87< clone 3< clone 68< clone 33); in subset 3 it ranged from 6.40 to 7.79 μm and clones were: (clone 72< clone 74< clone 45< clone 11< clone 90< clone 30< clone 73< clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49); in subset 4 it ranged from 6.70 to 8.16 μm and clones were: (clone 74< clone 45< clone 11< clone 90< clone 30< clone 73< clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12<); in subset 5 it ranged from 6.76 to 8.21 μm and clones were: (clone 45< clone 11< clone 90< clone 30< clone 73< clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55); in subset 6 it ranged from 6.97 to 8.42 μm and clones were: (clone 11< clone 90< clone 30< clone 73< clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone 51< clone 85< clone 46< clone 54); in subset 7 it ranged from 7.02 to 8.49 μm and clones were: (clone 90< clone 30< clone 73< clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone

60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone 51< clone 85< clone 46< clone 54); in subset 8 it ranged from 7.04 to 8.53 μm and clones were: (clone 30< clone 73< clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone 51< clone 85< clone 46< clone 54< clone 44< clone 5); in subset 9 it ranged from 7.13 to 8.61 μm and clones were: (clone 73< clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone 51< clone 85< clone 46< clone 54< clone 44< clone 5< clone 66); in subset 10 it ranged from 7.24 to 8.68 μm and clones were: (clone 87< clone 3< clone 68< clone 33< clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone 51< clone 85< clone 46< clone 54< clone 44< clone 5< clone 66< clone 25< clone 69); in subset 11 it ranged from 7.48 to8.88 μm and clones were: (clone 35< clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone 51< clone 85< clone 46< clone 54< clone 44< clone 5< clone 66< clone 25< clone 69< clone 88); in subset 12 it ranged from 07.55 to 9.00 and clones were: (clone 59< clone 60< clone 58< clone 1< clone 20< clone 62< clone 63< clone 47< clone 53< clone 49< clone 84< clone 31< clone 48< clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone 51< clone 85< clone 46< clone 54< clone 44< clone 5< clone 66< clone 25< clone 69< clone 88< clone 61); in subset 13 it ranged from 7.94 to 9.34 μm and clones were: (clone 86< clone 89< clone 36< clone 83< clone 12< clone 55< clone 64< clone

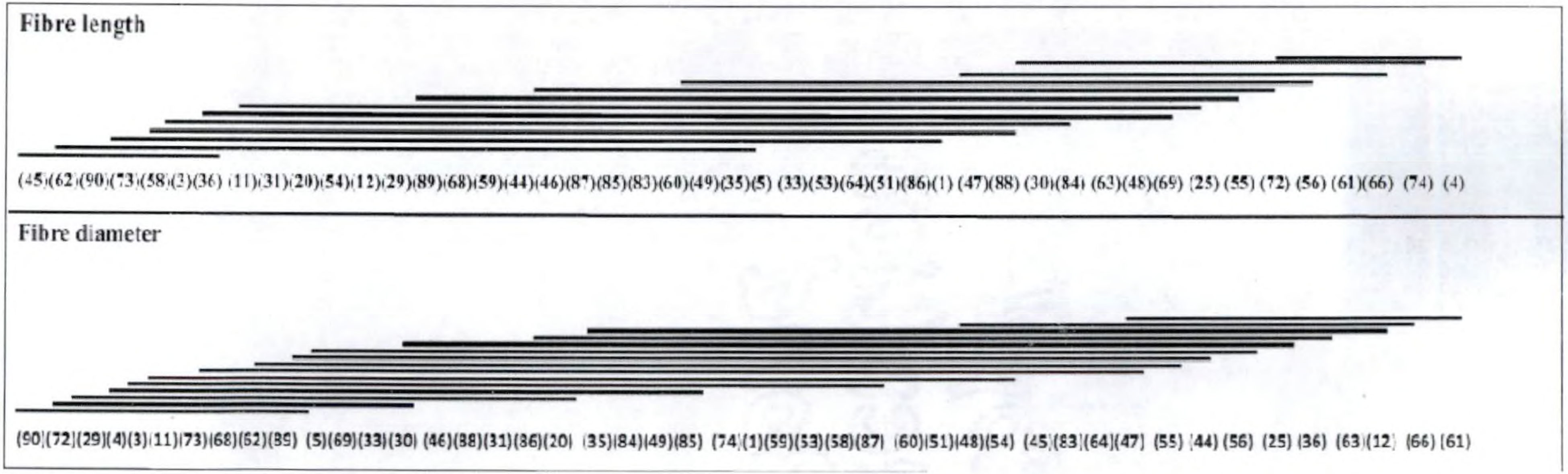
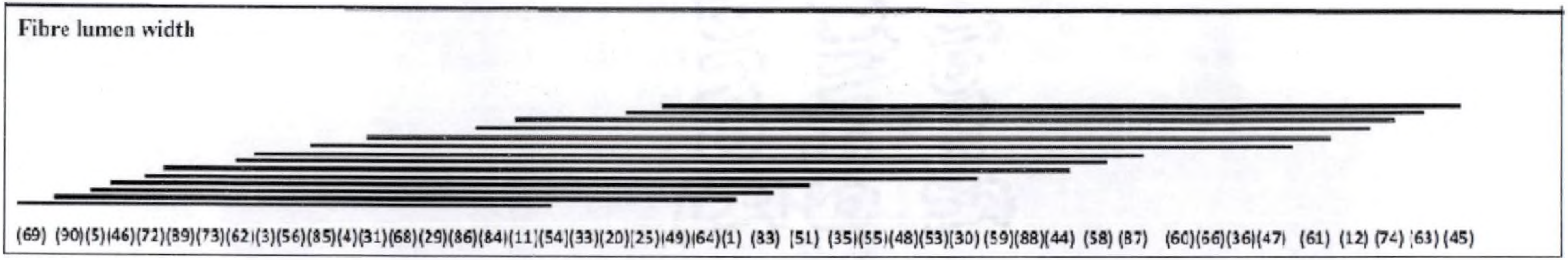


Fig.4. Bar diagram of all 47 trees on the basis of fibre dimensions-fibre length and fibre diameter.



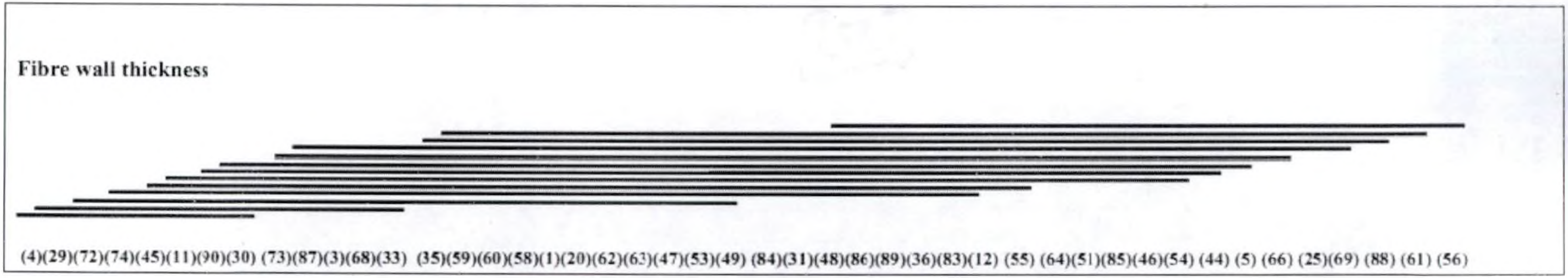


Fig.5. Bar diagram of all 47 trees on the basis of fibre lumen width and fibre wall thickness.

51< clone 85< clone 46< clone 54< clone 44< clone 5< clone 66< clone 25< clone 69< clone 88< clone 61< clone 56).

Table 3: Mean of fibre dimensions of the different clones.

Clone number	Fibre length (μm)	Fibre width (μm)	Fibre lumen width (μm)	Fibre wall thickness (μm)
Clone 1	1474.45 (37.078)	25.49 (0.57)	9.89 (0.62)	7.64 (0.36)
Clone 3	1348.83 (30.468)	22.71 (0.99)	8.30 (0.71)	7.27 (0.31)
Clone 4	1726.49 (52.884)	22.16 (1.01)	8.69 (1.14)	5.73 (0.67)
Clone 5	1457.65 (44.387)	24.00 (0.74)	7.11 (0.59)	8.53 (0.38)
Clone 11	1372.55 (24.200)	22.94 (0.84)	9.28 (0.86)	6.97 (0.44)
Clone 12	1387.22 (30.641)	28.23 (0.88)	11.97 (1.01)	8.16 (0.35)
Clone 20	1379.97 (32.294)	24.74 (1.05)	9.44 (0.63)	7.65 (0.46)
Clone 25	1527.27 (40.419)	27.52 (1.02)	9.54 (0.73)	8.64 (0.48)
Clone 29	1391.82 (85.137)	21.66 (1.07)	8.83 (0.88)	5.99 (0.59)
Clone 30	1500.57 (43.171)	24.30 (1.11)	10.26 (1.15)	7.04 (0.33)
Clone 31	1377.45 (57.602)	24.48 (0.43)	8.75 (0.79)	7.86 (0.40)
Clone 33	1463.73 (44.356)	24.23 (0.64)	9.40 (0.93)	7.33 (0.49)
Clone 35	1451.67 (27.211)	25.02 (0.89)	10.06 (0.86)	7.48 (0.39)
Clone 41	1360.48 (46.602)	27.58 (0.89)	11.35 (0.91)	8.07 (0.39)
Clone 44	1407.13 (52.083)	27.15 (0.99)	10.46 (0.67)	8.49 (0.33)
Clone 45	1225.60 (37.159)	26.16 (1.23)	12.53 (1.35)	6.76 (0.41)
Clone 46	1421.42 (51.481)	24.40 (0.98)	7.19 (0.53)	8.41 (0.39)
Clone 47	1484.00 (49.61)	26.62 (0.82)	11.36 (1.00)	7.77 (0.34)
Clone 48	1511.93 (58.686)	25.96 (1.01)	10.19 (0.79)	7.87 (0.52)

Clone 49	1449.83 (42.265)	25.12 (0.74)	9.69 (0.83)	7.79 (0.38)
Clone 51	1467.40 (47.518)	25.95 (0.76)	9.99 (1.02)	8.27 (0.57)
Clone 53	1464.80 (45.93)	25.59 (0.88)	10.21 (0.82)	7.79 (0.29)
Clone 54	1385.09 (41.608)	26.13 (0.94)	9.34 (0.83)	8.42 (0.44)
Clone 55	1549.40 (40.779)	26.79 (1.09)	10.08 (1.33)	8.21 (0.54)
Clone 56	1598.80 (38.102)	27.21 (0.70)	8.30 (0.87)	9.34 (0.45)
Clone 58	1342.20 (35.781)	25.75 (1.45)	10.74 (1.25)	7.57 (0.35)
Clone 59	1406.75 (41.081)	25.49 (1.27)	10.39 (1.24)	7.55 (0.25)
Clone 60	1442.48 (32.481)	25.93 (1.10)	11.28 (0.90)	7.57 (0.54)
Clone 61	1627.17 (52.221)	29.61 (1.53)	11.61 (0.93)	9.00 (0.52)
Clone 62	1304.87 (36.885)	23.59 (0.83)	7.88 (0.62)	7.69 (0.23)
Clone 63	1510.53 (34.011)	27.75 (0.73)	12.32 (0.96)	7.70 (0.45)
Clone 64	1466.48 (27.63)	26.51 (1.14)	9.84 (1.16)	8.26 (0.34)
Clone 66	1629.12 (80.581)	29.05 (0.81)	17.98 (6.78)	8.61 (0.56)
Clone 68	1401.02 (50.403)	23.56 (0.57)	8.79 (0.60)	7.32 (0.29)
Clone 69	1512.25 (60.176)	24.08 (0.84)	6.57 (0.43)	8.68 (0.27)
Clone 72	1572.47 (63.185)	21.33 (1.01)	7.47 (0.78)	6.40 (0.48)
Clone 73	1325.01 (37.669)	22.94 (0.64)	7.78 (0.73)	7.13 (0.32)
Clone 74	1636.90 (52.894)	25.40 (0.91)	12.09 (0.64)	6.70 (0.34)
Clone 83	1429.45 (41.778)	26.32 (0.91)	9.92 (1.00)	8.13 (0.48)
Clone 84	1502.48 (42.152)	25.09 (0.74)	9.13 (0.93)	7.86 (0.52)
Clone 85	1426.87 (30.995)	25.26 (0.97)	8.55 (0.76)	8.35 (0.37)

Clone 86	1469.85 (41.761)	24.54 (0.9)	8.86 (0.85)	7.94 (0.43)
Clone 87	1425.85 (26.779)	25.79 (1.09)	11.08 (1.15)	7.24 (0.42)
Clone 88	1487.83 (34.859)	24.46 (0.83)	10.41 (1.03)	8.88 (0.98)
Clone 89	1397.07 (38.599)	23.61 (1.08)	7.69 (0.73)	8.03 (0.31)
Clone 90	1308.52 (43.78)	20.69 (0.50)	7.05 (0.46)	7.02 (0.29)
Total	**1452.41 (12.64)**	**25.193 (0.153)**	**9.630 (0.141)**	**7.763 (0.69)**

(Value in parenthesis is standard error of mean)

4.1.2.1b. Within clone variation

Table 4 shows pooled mean values of 46 clones at different height for different wood traits. Average tree fiber length (μm) for different heights ranged from 1451.36 (middle) to 1473.15 (base); fibre width (μm) from 24.917 (middle) to 25.483 (top); fibre lumen width from 9.209 (middle) to 10.081 (top); and fibre cell wall thickness from 7.824 (top) to 7.690 (base). All the parameters were lowest at middle position except fibre wall thickness. Parameters like fibre length, fibre width and fibre lumen width showed initial decrease from base to middle and then increasing upwards (figure 6A, 6B & 7A). Instead of this, fibre wall thickness showed initial increase from base to middle and then decreasing upwards (figure 7A).

Table 4: Mean of fibre dimensions of the clones at different heights.

Positions	Fibre length (μm)	Fibre width (μm)	Fibre lumen width (μm)	Fibre wall thickness (μm)
Base	1473.15 (12.64)	25.180 (0.279)	9.600 (0.242)	7.690 (0.118)
Middle	1451.36 (12.94)	24.917 (0.243)	9.209 (0.224)	7.777 (0.111)
Top	1454.45 (13.09)	25.483 (0.271)	10.081 (0.262)	7.824 (0.129)
Mean	1459.65 (7.43)	25.194 (0.153)	9.6301 (0.141)	7.763 (0.069)

(Value in parenthesis is standard error of mean)

Fig. A

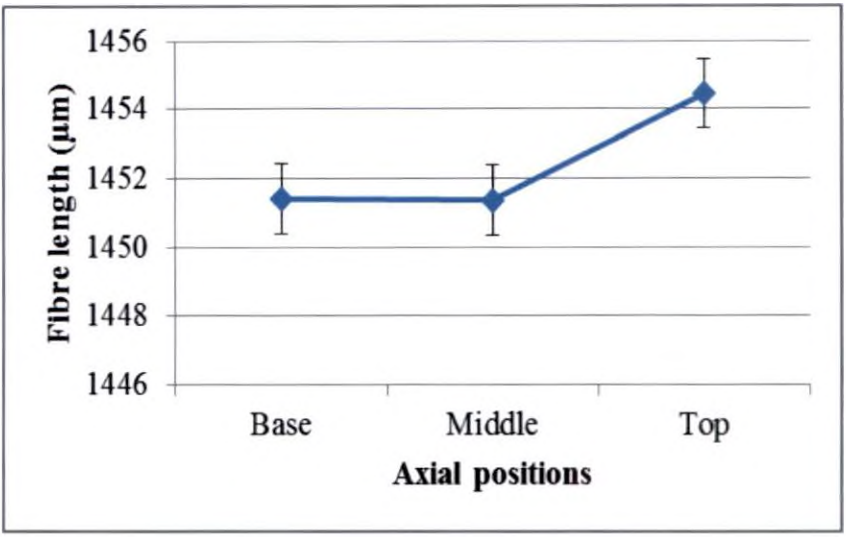


Fig. B

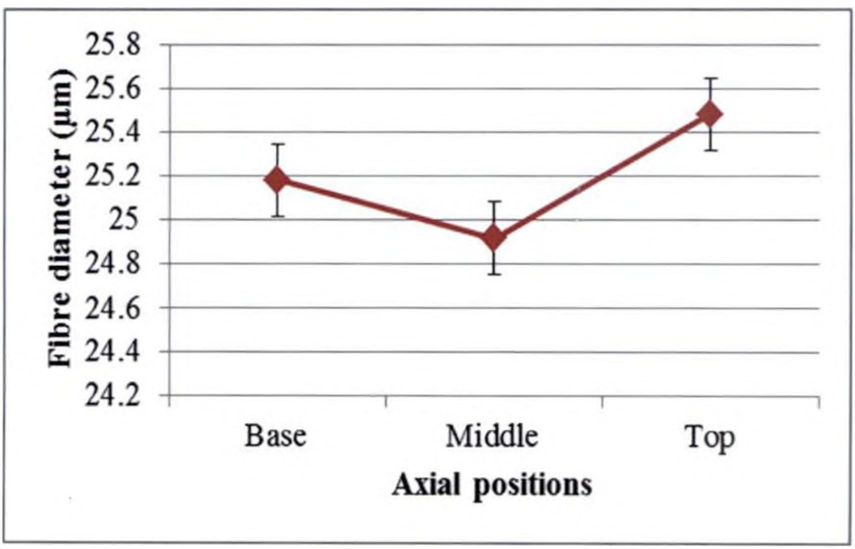


Fig.6. Axial variation of (A) fibre length; (B) fibre diameter and (C) fibre lumen width of clones.

Fig. A

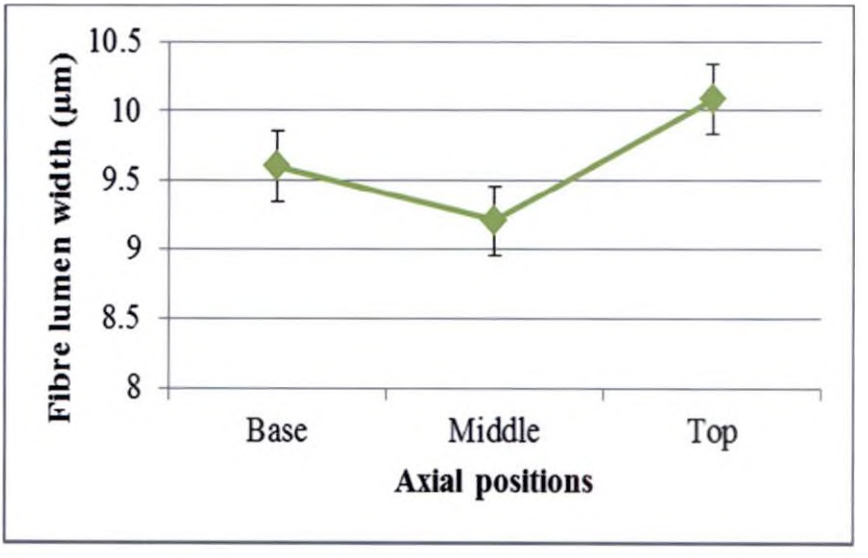


Fig. B

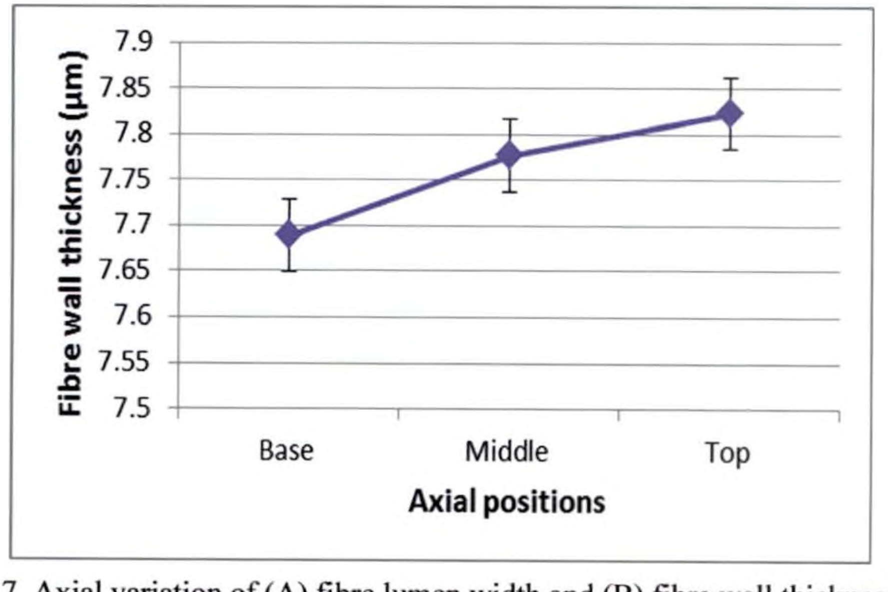


Fig.7. Axial variation of (A) fibre lumen width and (B) fibre wall thickness of clones.

4.1.2.2 Ratios and factors

4.1.2.2a. Variation among clones

Among various ratios and factors studied *i.e.* Runkel ratio, slenderness ratio, rigidity coefficient, flexibility coefficient and shape factor, only slenderness ratio showed significant inter clonal variation. Table 5 shows mean Runkel ratio ranged in 46 clones from 1.159 (clone 74) to 2.830 (clone 69); slenderness ratio from 97.716 (clone 45) to 161.72 (clone 4); rigidity coefficient from 51.309 (clone 4) to 72.532 (clone 69); flexibility coefficient from 54.161 (clone 69) to 95.421 (clone 74); and shape factor from 0.638 (clone 74) to 0.860 (clone 69).

On the basis of Runkel ratio all 46 clones were divided into 9 different subsets (figure 6). In the subset 1 runkel ratio ranged from 1.16 to 1.89 and clones were: (clone 74< clone 45< clone 63< clone 60< clone 12< clone 29< clone 47< clone 87< clone 36< clone 53< clone 35< clone 61< clone 58< clone 20< clone 44< clone 11< clone 1< clone 48< clone 59< clone 4< clone 68< clone 88< clone 33< clone 30< clone 66< clone 49); in subset 2 it ranged from 1.3 to 2.12 and the clones were: (clone 45< clone 63< clone 60< clone 12< clone 29< clone 47< clone 87< clone 36< clone 53< clone 35< clone 61< clone 58< clone 20< clone 44< clone 11< clone 1< clone 48< clone 59< clone 4< clone 68< clone 88< clone 33< clone 30< clone 66< clone 49< clone 3< clone 51< clone 64< clone 83< clone 25< clone 86< clone 54< clone 72< clone 55< clone 84< clone 73); in subset 3 it ranged from 1.42 to 2.15 and clones were: (clone 63< clone 60< clone 12< clone 29< clone 47< clone 87< clone 36< clone 53< clone 35< clone 61< clone 58< clone 20< clone 44< clone 11< clone 1< clone 48< clone 59< clone 4< clone 68< clone 88< clone 33< clone 30< clone 66< clone 49< clone 3< clone 51< clone 64< clone 83< clone 25< clone 86< clone 54< clone 72< clone 55< clone 84< clone 73< clone 31< clone 62< clone 90); in subset 4 it ranged from 1.49 to 2.18 and clones were: (clone 60< clone 12< clone 29< clone 47< clone 87< clone 36< clone 53< clone 35< clone 61< clone 58< clone 20< clone 44< clone 11< clone 1< clone 48< clone 59< clone 4< clone 68< clone 88< clone 33< clone 30< clone 66< clone 49< clone 3< clone 51< clone 64< clone 83< clone

25< clone 86< clone 54< clone 72< clone 55< clone 84< clone 73< clone 31< clone 62< clone 90< clone 85); in subset 5 it ranged from 1.59 to 2.32 and clones were: (<clone 36< clone 53< clone 35< clone 61< clone 58< clone 20< clone 44< clone 11< clone 1< clone 48< clone 59< clone 4< clone 68< clone 88< clone 33< clone 30< clone 66< clone 49< clone 3< clone 51< clone 64< clone 83< clone 25< clone 86< clone 54< clone 72< clone 55< clone 84< clone 73< clone 31< clone 62< clone 90< clone 85< clone 89); in subset 6 it ranged from 1.84 to 2.53 and clones were: (clone 88< clone 33< clone 30< clone 66< clone 49< clone 3< clone 51< clone 64< clone 83< clone 25< clone 86< clone 54< clone 72< clone 55< clone 84< clone 73< clone 31< clone 62< clone 90< clone 85< clone 89< clone 46); in subset 7 it ranged from 1.96 to 2.63 and clones were: (clone 3< clone 51< clone 64< clone 83< clone 25< clone 86< clone 54< clone 72< clone 55< clone 84< clone 73< clone 31< clone 62< clone 90< clone 85< clone 89< clone 46< clone 56); in subset 8 it ranged from 2.12 to 2.80 and clones were: (< clone 73< clone 31< clone 62< clone 90< clone 85< clone 89< clone 46< clone 56< clone 5); in subset 9 it ranged from 2.18 to 2.83 and clones were: (clone 85< clone 89< clone 46< clone 56< clone 5< clone 69).

On the basis of slenderness ratio all 46 clones were divided into 7 different subsets (figure 6). In the subset 1 slenderness ratio ranged from 97.72 to117.91 and clones were: (clone 45< clone 12< clone 36< clone 54< clone 63< clone 58< clone 44< clone 83< clone 25< clone 47< clone 66< clone 62< clone 87< clone 61< clone 31< clone 64< clone 60< clone 51< clone 20< clone 59< clone 85< clone 53< clone 1< clone 49< clone 73< clone 56); in subset 2 it ranged from 99.58 to 119.67 and the clones were: (clone 12< clone 36< clone 54< clone 63< clone 58< clone 44< clone 83< clone 25< clone 47< clone 66< clone 62< clone 87< clone 61< clone 31< clone 64< clone 60< clone 51< clone 20< clone 59< clone 85< clone 53< clone 1< clone 49< clone 73< clone 56< clone 46< clone 35< clone 55< clone 48< clone 68); in subset 3 it ranged from 100.64 to 121.65 and clones were: (clone 36< clone 54< clone 63< clone 58< clone 44< clone 83< clone 25< clone 47< clone 66< clone 62< clone 87< clone 61< clone 31< clone 64< clone 60< clone 51< clone 20< clone 59< clone 85< clone 53< clone 1<

clone 49< clone 73< clone 56< clone 46< clone 35< clone 55< clone 48< clone 68< clone 11< clone 86< clone 84< clone 89); in subset 4 it ranged from 107.88 to 127.84 and clones were: (clone 54< clone 63< clone 58< clone 44< clone 83< clone 25< clone 47< clone 66< clone 62< clone 87< clone 61< clone 31< clone 64< clone 60< clone 51< clone 20< clone 59< clone 85< clone 53< clone 1< clone 49< clone 73< clone 56< clone 46< clone 35< clone 55< clone 48< clone 68< clone 11< clone 86< clone 84< clone 89< clone 3< clone 33< clone 5< clone 88< clone 30< clone 90< clone 69); in subset 5 it ranged from 112.19 to 132.59 and clones were: (clone 25< clone 47< clone 66< clone 62< clone 87< clone 61< clone 31< clone 64< clone 60< clone 51< clone 20< clone 59< clone 85< clone 53< clone 1< clone 49< clone 73< clone 56< clone 46< clone 35< clone 55< clone 48< clone 68< clone 11< clone 86< clone 84< clone 89< clone 3< clone 33< clone 5< clone 88< clone 30< clone 90< clone 69< clone 74); in subset 6 it ranged from 114.14 to 134.81 and clones were: (clone 60< clone 51< clone 20< clone 59< clone 85< clone 53< clone 1< clone 49< clone 73< clone 56< clone 46< clone 35< clone 55< clone 48< clone 68< clone 11< clone 86< clone 84< clone 89< clone 3< clone 33< clone 5< clone 88< clone 30< clone 90< clone 69< clone 74< clone 29); in subset 7 it ranged from 152.56 to 161.17 and clones were: (clone 72< clone 4).

On the basis of rigidity coefficient all 46 clones were divided into 11 different subsets (figure 7). In the subset 1 rigidity coefficient ranged from 51.31 to 60.68 and clones were: (clone 4< clone 74< clone 45< clone 29< clone 63< clone 87< clone 60< clone 12< clone 36< clone 47< clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone 59); in subset 2 it ranged from 52.81 to 62.30 and the clones were: (clone 74< clone 45< clone 29< clone 63< clone 87< clone 60< clone 12< clone 36< clone 47< clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone 59< clone 11< clone 61< clone 53< clone 20< clone 55< clone 83< clone 73< clone 49< clone 68); in subset 3 it ranged from 54.61 to 64.32 and clones were: (clone 29< clone 63< clone 87< clone 60< clone 12< clone 36< clone 47< clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone

59< clone 11< clone 61< clone 53< clone 20< clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31); in subset 4 it ranged from 55.71 to 65.15 and clones were: (clone 63< clone 87< clone 60< clone 12< clone 36< clone 47< clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone 59< clone 11< clone 61< clone 53< clone 20< clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31< clone 3< clone 54< clone 86); in subset 5 it ranged from 56.82 to 66.53 and clones were: (clone 87< clone 60< clone 12< clone 36< clone 47< clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone 59< clone 11< clone 61< clone 53< clone 20< clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31< clone 3< clone 54< clone 86< clone 62< clone 85); in subset 6 it ranged from 58.36 to 67.75 and clones were: (< clone 60< clone 12< clone 36< clone 47< clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone 59< clone 11< clone 61< clone 53< clone 20< clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31< clone 3< clone 54< clone 86< clone 62< clone 85< clone 90); in subset 7 it ranged from 59.06 to 68.75 and clones were: (clone 47< clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone 59< clone 11< clone 61< clone 53< clone 20< clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31< clone 3< clone 54< clone 86< clone 62< clone 85< clone 90< clone 56); in subset 8 it ranged from 59.47 to 69.17 and clones were: (clone 30< clone 1< clone 72< clone 66< clone 35< clone 48< clone 58< clone 33< clone 59< clone 11< clone 61< clone 53< clone 20< clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31< clone 3< clone 54< clone 86< clone 62< clone 85< clone 90< clone 56< clone 89< clone 46); in subset 9 it ranged from 61.60 to 71.07 and clones were: (clone 20< clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31< clone 3< clone 54< clone 86< clone 62< clone 85< clone 90<

clone 56< clone 89< clone 46< clone 5); in subset 10 it ranged from 62.12 to 71.35 and clones were: (clone 55< clone 83< clone 73< clone 49< clone 68< clone 84< clone 44< clone 25< clone 51< clone 64< clone 31< clone 3< clone 54< clone 86< clone 62< clone 85< clone 90< clone 56< clone 89< clone 46< clone 5< clone 88); in subset 11 it ranged from 63.21 to 72.35 and clones were: (clone 51< clone 64< clone 31< clone 3< clone 54< clone 86< clone 62< clone 85< clone 90< clone 56< clone 89< clone 46< clone 5< clone 88< clone 69).

On the basis of flexibility coefficient all 46 clones were divided into 11 different subsets (figure 7). In the subset I flexibility coefficient ranged from 54.16 to 71.24 and clones were: (clone 69< clone 46< clone 5< clone 56< clone 89< clone 62< clone 85< clone 73< clone 90< clone 25< clone 72< clone 54< clone 31); in subset 2 it ranged from 58.60 to 74.87 and the clones were: (clone 46< clone 5< clone 56< clone 89< clone 62< clone 85< clone 73< clone 90< clone 25< clone 72< clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83); in subset 3 it ranged from 59.14 to76.87 and clones were: (clone 5< clone 56< clone 89< clone 62< clone 85< clone 73< clone 90< clone 25< clone 72< clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83< clone 20< clone 44< clone 66< clone 49); in subset 4 it ranged from 60.66 to 78.32 and clones were: (clone 56< clone 89< clone 62< clone 85< clone 73< clone 90< clone 25< clone 72< clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83< clone 20< clone 44< clone 66< clone 49< clone 33< clone 51< clone 1< clone 4< clone 61< clone 59); in subset 5 it ranged from 64.13 to 81.63 and clones were: (clone 89< clone 62< clone 85< clone 73< clone 90< clone 25< clone 72< clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83< clone 20< clone 44< clone 66< clone 49< clone 33< clone 51< clone 1< clone 4< clone 61< clone 59< clone 48< clone 53< clone 35< clone 11< clone 58< clone 29< clone 30< clone 36); in subset 6 it ranged from 65.80 to 84.03 and clones were: (clone 62< clone 85< clone 73< clone 90< clone 25< clone 72< clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83< clone 20< clone 44< clone 66< clone 49< clone 33<

clone 51< clone 1< clone 4< clone 61< clone 59< clone 48< clone 53< clone 35< clone 11< clone 58< clone 29< clone 30< clone 36< clone 88< clone 12< clone 47); in subset 7 it ranged from 66.80 to 84.52 and clones were: (clone 85< clone 73< clone 90< clone 25< clone 72< clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83< clone 20< clone 44< clone 66< clone 49< clone 33< clone 51< clone 1< clone 4< clone 61< clone 59< clone 48< clone 53< clone 35< clone 11< clone 58< clone 29< clone 30< clone 36< clone 88< clone 12< clone 47< clone 87); in subset 8 it ranged from 69.60 to 86.83 and clones were: (clone 25< clone 72< clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83< clone 20< clone 44< clone 66< clone 49< clone 33< clone 51< clone 1< clone 4< clone 61< clone 59< clone 48< clone 53< clone 35< clone 11< clone 58< clone 29< clone 30< clone 36< clone 88< clone 12< clone 47< clone 87< clone 60); in subset 9 it ranged from 70.96 to 88.57 and clones were: (clone 54< clone 31< clone 86< clone 3< clone 64< clone 84< clone 55< clone 68< clone 83< clone 20< clone 44< clone 66< clone 49< clone 33< clone 51< clone 1< clone 4< clone 61< clone 59< clone 48< clone 53< clone 35< clone 11< clone 58< clone 29< clone 30< clone 36< clone 88< clone 12< clone 47< clone 87< clone 60< clone 63); in subset 10 it ranged from 76.56 to 92.91 and clones were: (clone 20< clone 44< clone 66< clone 49< clone 33< clone 51< clone 1< clone 4< clone 61< clone 59< clone 48< clone 53< clone 35< clone 11< clone 58< clone 29< clone 30< clone 36< clone 88< clone 12< clone 47< clone 87< clone 60< clone 63< clone 45); in subset 11 it ranged from 78.16 to 95.42 and clones were: (clone 61< clone 59< clone 48< clone 53< clone 35< clone 11< clone 58< clone 29< clone 30< clone 36< clone 88< clone 12< clone 47< clone 87< clone 60< clone 63< clone 45< clone 74).

On the basis of shape factor all 46 clones were divided into 11 different subsets (figure 7). In the subset 1 shape factor ranged from 0.6572 to 0.7298 and clones were: (clone 74< clone 45< clone 63< clone 60< clone 87< clone 47< clone 88< clone 12< clone 30< clone 29< clone 36< clone 58< clone 11< clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33); in subset 2 it ranged from 0.6366 to 0.7402 and the clones were: (clone 45< clone 63< clone 60< clone 87< clone 47< clone 88< clone 12< clone 30< clone 29< clone 36< clone 58< clone 11< clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20); in subset 3 it ranged from 0.6659 to0.7686 and clones were: (clone 63< clone 60< clone 87< clone 47< clone 88< clone 12< clone 30< clone 29< clone 36< clone 58< clone 11< clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54); in subset 4 it ranged from 0.6771 to 0.7766 and clones were: (clone 60< clone 87< clone 47< clone 88< clone 12< clone 30< clone 29< clone 36< clone 58< clone 11< clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25); in subset 5 it ranged from 0.6886 to0.7929 and clones were: (clone 87< clone 47< clone 88< clone 12< clone 30< clone 29< clone 36< clone 58< clone 11< clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25< clone 90< clone 73< clone 85); in subset 6 it ranged from 0.6948 to 0.7997 and clones were: (clone 47< clone 88< clone 12< clone 30< clone 29< clone 36< clone 58< clone 11< clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25< clone 90< clone 73< clone 85< clone 62); in subset 7 it ranged from 0.7065 to 0.8075 and clones were: (clone 29< clone 36< clone 58< clone 11< clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25< clone 90< clone 73< clone 85< clone 62< clone 89); in subset 8 it ranged from 0.7216 to

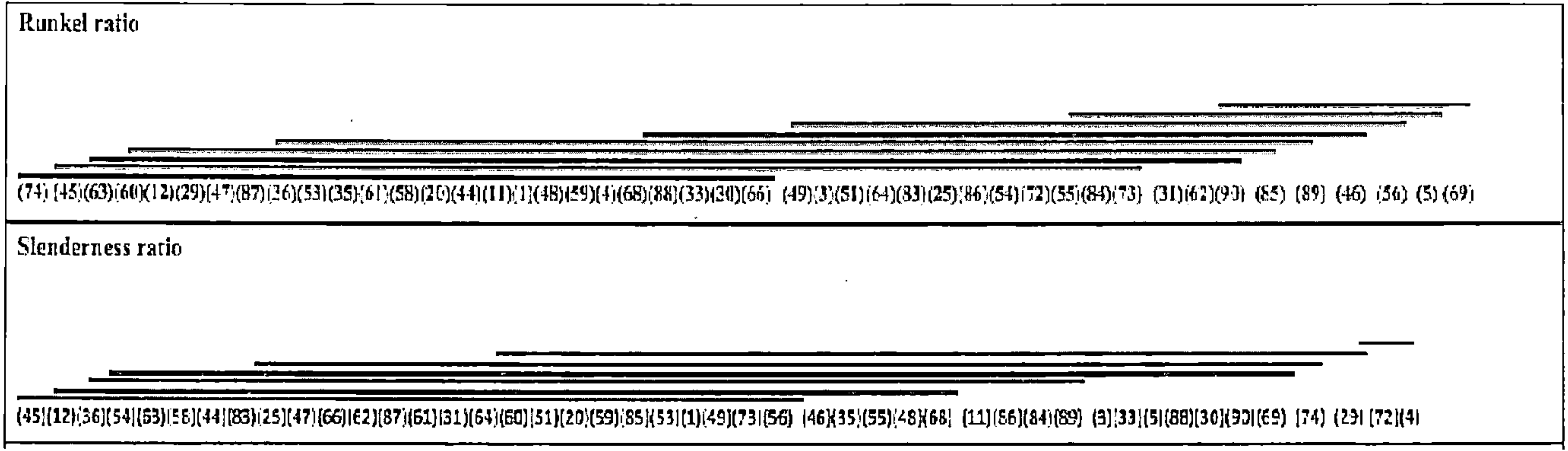


Fig.8. Bar diagram of all 47 trees on the basis of Runkel ratio and slenderness ratio.

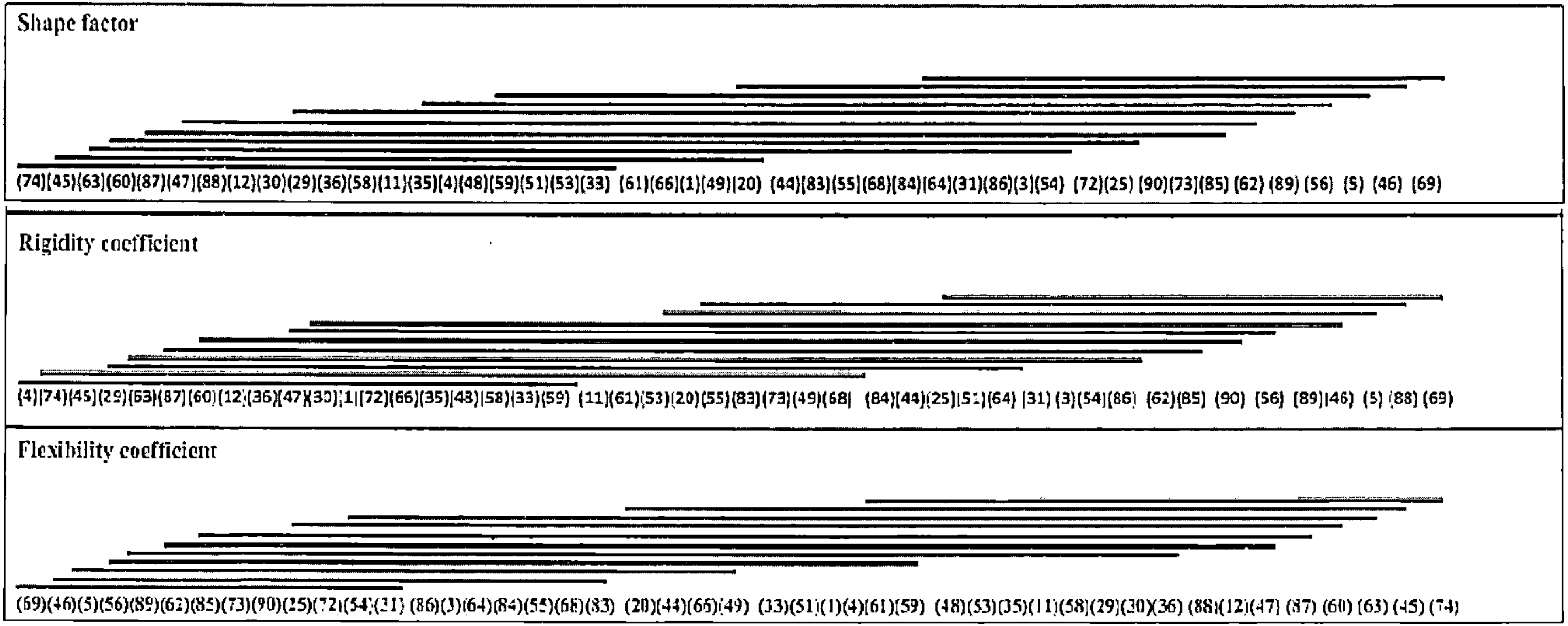


Fig.9. Bar diagram of all 47 trees on the basis of shape factor, rigidity coefficient and flexibility coefficient.

0.8205 and clones were: (clone 35< clone 4< clone 48< clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25< clone 90< clone 73< clone 85< clone 62< clone 89< clone 56); in subset 9 it ranged from 0.7261 to 0.8303 and clones were: (clone 59< clone 51< clone 53< clone 33< clone 61< clone 66< clone 1< clone 49< clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25< clone 90< clone 73< clone 85< clone 62< clone 89< clone 56< clone 5); in subset 10 it ranged from 0.7402 to 0.8372 and clones were: (clone 20< clone 44< clone 83< clone 55< clone 68< clone 84< clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25< clone 90< clone 73< clone 85< clone 62< clone 89< clone 56< clone 5< clone 46); in subset 11 it ranged from 0.7622 to 0.8602 and clones were: (clone 64< clone 31< clone 86< clone 3< clone 54< clone 72< clone 25< clone 90< clone 73< clone 85< clone 62< clone 89< clone 56< clone 5< clone 46< clone 69).

Table 5: Mean fibre dimension ratios and factors of different clones

Clone no.	Runkel ratio	Slenderness ratio	Rigidity coefficient	Flexibility coefficient	Shape factor
Clone 1	1.74 (0.235)	116.74 (4.57)	60.00 (2.71)	77.54 (4.65)	0.732 (0.025)
Clone 3	1.96 (0.222)	122.43 (6.46)	64.54 (2.30)	72.02 (4.04)	0.765 (0.022)
Clone 4	1.78 (0.352)	162.70 (9.76)	56.16 (4.80)	77.66 (8.47)	0.722 (0.049)
Clone 5	2.80 (0.380)	123.37 (5.81)	71.07 (2.39)	59.14 (4.66)	0.830 (0.022)
Clone 11	1.74 (0.212)	121.23 (3.76)	60.9 1(3.03)	80.28 (6.35)	0.714 (0.038)
Clone 12	1.55 (0.174)	99.58 (3.62)	58.57 (2.92)	83.56 (5.17)	0.697 (0.031)
Clone 20	1.72 (0.139)	114.42 (5.57)	61.6 (2.50)	76.56 (4.60)	0.740 (0.028)
Clone 25	2.02 (0.226)	112.19 (3.33)	62.89 (2.94)	69.60 (5.09)	0.777 (0.029)

Clone 29	1.55 (0.205)	134.81 (4.23)	54.61 (3.71)	81.38 (6.42)	0.707 (0.037)
Clone 30	1.88 (0.371)	126.04 (5.07)	59.47 (3.78)	81.56 (7.12)	0.702 (0.039)
Clone 31	2.13 (0.280)	113.34 (5.58)	64.32 (3.17)	71.24 (6.13)	0.764 (0.034)
Clone 33	1.86 (0.241)	122.50 (5.84)	60.59 (3.83)	77.26 (6.86)	0.730 (0.040)
Clone 35	1.65 (0.150)	118.74 (6.06)	60.23 (2.80)	79.55 (5.37)	0.722 (0.033)
Clone 41	1.59 (0.175)	100.64 (5.41)	58.96 (2.85)	81.63 (5.09)	0.709 (0.030)
Clone 44	1.72 (0.137)	110.35 (5.94)	62.86 (1.94)	76.62 (3.33)	0.741 (0.019)
Clone 45	1.37 (0.218)	97.72 (6.78)	53.02 (3.74)	92.91 (7.14)	0.637 (0.043)
Clone 46	2.53 (0.210)	118.65 (5.87)	69.17 (1.90)	58.60 (3.44)	0.837 (0.017)
Clone 47	1.55 (0.162)	112.60 (4.58)	59.06 (2.88)	84.03 (5.63)	0.695 (0.034)
Clone 48	1.74 (0.216)	119.54 (7.38)	60.32 (2.69)	78.71 (5.65)	0.724 (0.032)
Clone 49	1.89 (0.284)	116.74 (4.77)	62.30 (2.81)	76.87 (5.80)	0.734 (0.033)
Clone 51	1.97 (0.252)	114.21 (4.65)	63.21 (3.61)	77.45 (8.00)	0.726 (0.048)
Clone 53	1.65 (0.130)	115.81 (4.25)	61.28 (2.08)	78.86 (4.20)	0.727 (0.025)
Clone 54	2.06 (0.241)	107.88 (4.87)	64.88 (2.83)	70.96 (5.13)	0.769 (0.028)
Clone 55	2.07 (0.285)	118.79 (6.35)	62.12 (3.96)	73.61 (7.46)	0.748 (0.043)
Clone 56	2.63 (0.286)	117.91 (2.38)	68.75 (2.94)	60.66 (5.87)	0.820 (0.032)
Clone 58	1.72 (0.228)	109.95 (8.15)	60.33 (3.10)	80.48 (5.94)	0.713 (0.035)
Clone 59	1.75 (0.197)	114.45 (6.57)	60.68 (2.77)	78.32 (6.04)	0.726 (0.036)
Clone 60	1.49 (0.162)	114.14 (5.60)	58.36 (3.01)	86.83 (5.98)	0.677 (0.037)
Clone 61	1.67 (0.148)	113.11 (5.77)	61.02 (2.22)	78.16 (4.34)	0.731 (0.025)
Clone 62	2.14 (0.186)	112.78 (5.52)	65.79 (1.84)	65.80 (3.89)	0.800 (0.021)

Clone 63	1.42 (0.177)	109.94 (3.86)	55.71 (3.19)	88.57 (6.26)	0.666 (0.038)
Clone 64	1.98 (0.207)	113.75 (5.62)	63.38 (2.76)	72.08 (5.61)	0.762 (0.032)
Clone 66	1.79 (0.255)	112.75 (5.61)	60.09 (4.20)	76.79 (7.54)	0.732 (0.045)
Clone 68	1.89 (0.151)	119.67 (4.82)	62.30 (2.21)	74.35 (4.26)	0.753 (0.025)
Clone 69	2.83 (0.244)	127.84 (6.80)	72.35 (1.30)	54.16 (2.63)	0.860 (0.012)
Clone 72	2.07 (0.290)	152.56 (10.29)	60.05 (3.23)	69.64 (6.22)	0.772 (0.034)
Clone 73	2.12 (0.249)	117.12 (5.30)	62.21 (2.42)	67.31 (5.42)	0.787 (0.029)
Clone 74	1.16 (0.090)	132.59 (7.95)	52.81 (1.94)	95.42 (4.04)	0.627 (0.025)
Clone 83	2.02 (0.295)	110.66 (5.15)	62.18 (3.46)	74.87 (6.99)	0.742 (0.04)
Clone 84	2.08 (0.313)	121.60 (5.73)	62.74 (3.63)	72.49 (6.53)	0.757 (0.037)
Clone 85	2.18 (0.208)	114.51 (3.52)	66.53 (2.32)	66.80 (4.44)	0.793 (0.024)
Clone 86	2.03 (0.224)	121.56 (4.81)	65.15 (2.95)	71.80 (5.37)	0.765 (0.031)
Clone 87	1.56 (0.200)	112.96 (4.80)	56.82 (3.27)	84.52 (6.89)	0.689 (0.042)
Clone 88	1.84 (0.165)	123.52 (4.94)	71.35 (5.99)	83.39 (6.52)	0.696 (0.039)
Clone 89	2.32 (0.189)	121.65 (6.03)	68.86 (2.25)	64.13 (4.34)	0.808 (0.024)
Clone 90	2.15 (0.200)	127.72 (5.64)	67.75 (2.10)	68.23 (4.31)	0.786 (0.024)
Total	**1.900 (0.035)**	**118.31 (0.960)**	**62.01 (0.470)**	**75.49 (0.870)**	**0.742 (0.005)**

(Values in parenthesis is standard error of mean)

4.1.2.2b. Within clone variation

Analysis of variance showed that all the fibre dimension ratios and factors have significant within clone variation. Table 6 shows mean tree Runkel ratio for different heights ranged from 1.86 (top) to 1.96 (middle); slenderness ratio from 117.47 (top) to 119.12 (middle); rigidity coefficient from 61.44 (base) to 62.67 (middle); flexibility coefficient from 73.31 (middle) to 77.88 (top); and shape

Fig. A

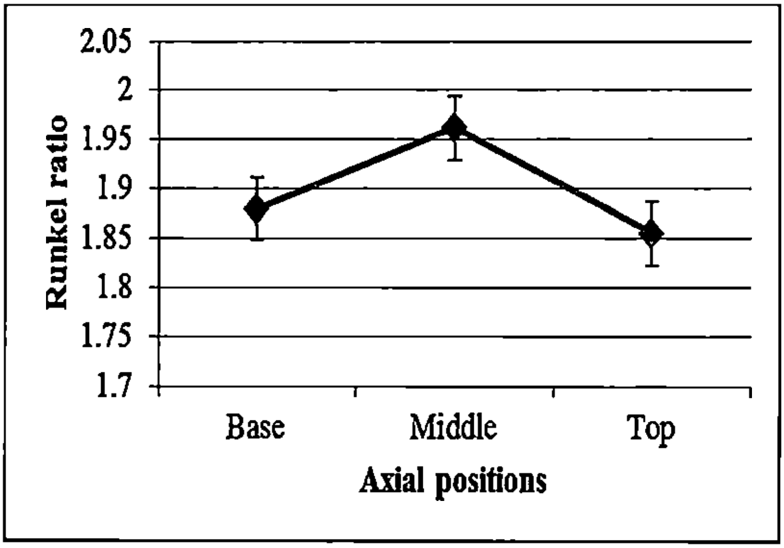


Fig. B

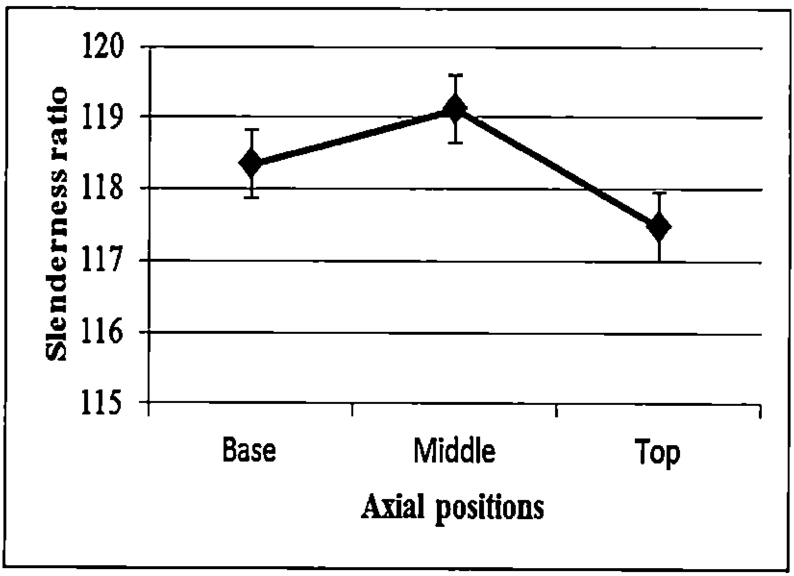


Fig.10. Axial variation of (A) Runkel ratio and (B) slenderness ratio

Fig. A

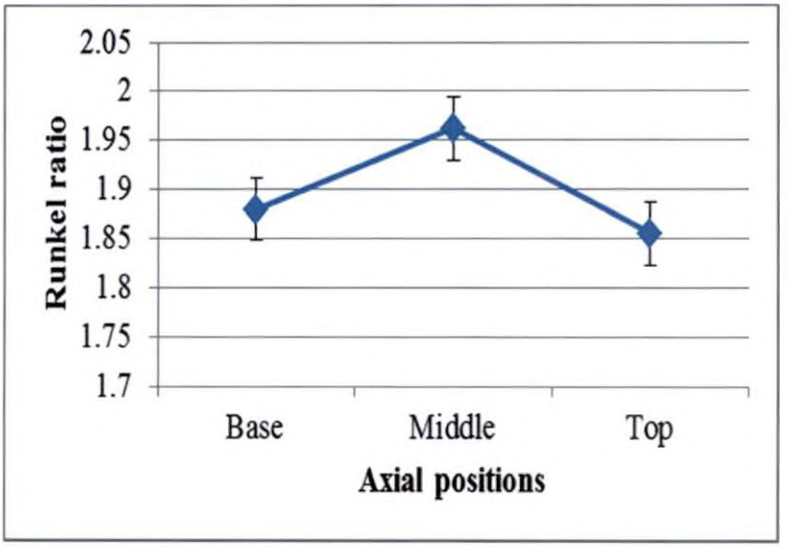


Fig. B

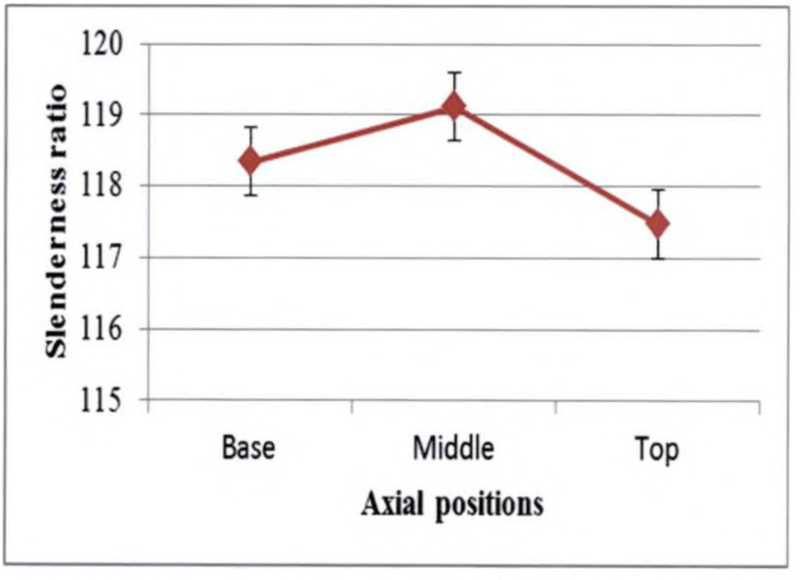


Fig.10. Axial variation of (A) Runkel ratio and (B) slenderness ratio

Fig. A

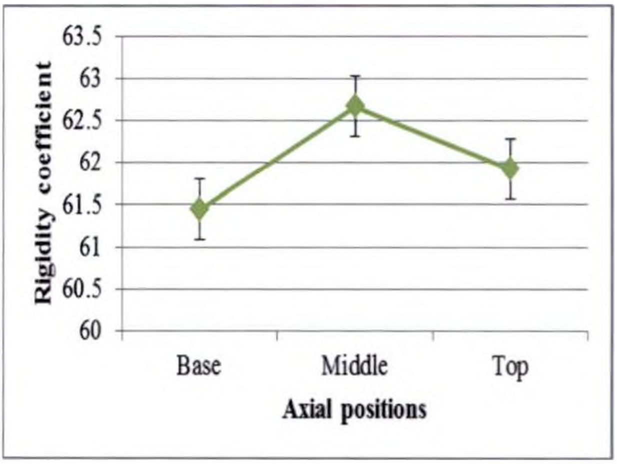


Fig. B

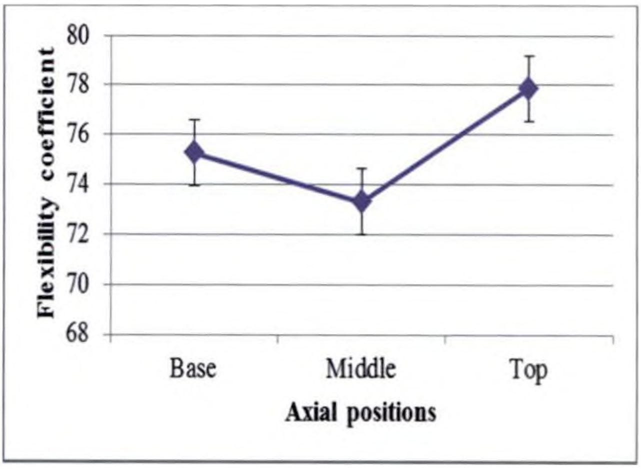


Fig. C

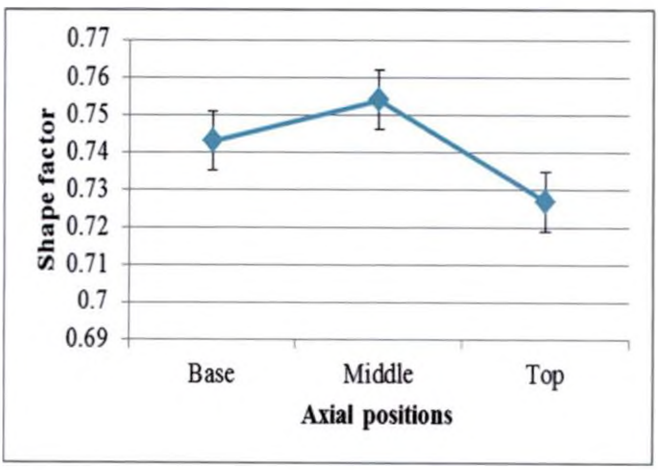


Fig.11. Axial variation of (A) rigidity coefficient (B) flexibility coefficient and (C) shape factor of clones

factor from 0.727 (top) to 0.754 (middle). As ratios and factors were derived from different fibre dimensional parameters, significant variation in fibre dimensions reflected in these ratios and factors. All the fibre derived ratios and factors except flexibility coefficient were increasing from base to middle and then decreasing towards the top. Flexibility coefficient increased from base to top after a small initial decrease from base to middle (figure 10 & 11).

Table 6: Mean fibre dimension ratios and factors at different heights.

Positions	Runkel ratio	Slenderness ratio	Rigidity coefficient	Flexibility coefficient	Shape facto
Base	1.88 (0.061)	118.34 (1.514)	61.44 (0.791)	75.27 (1.472)	0.743 (0.018)
Middle	1.96 (0.061)	119.12 (1.634)	62.67 (0.736)	73.31 (1.453)	0.754 (0.008)
Top	1.86 (0.062)	117.47 (1.852)	61.92 (0.909)	77.88 (1.603)	0.727 (0.009)
Mean	1.90 (0.035)	118.31 (0.305)	62.01 (0.470)	76.38 (0.874)	0.742 (0.005)

(Value in parenthesis is standard error of mean)

4.1.2.3 Vessel and ray morphology

4.1.2.3a. Variation among clones

All the vessel and ray parameters showed significant inter-clonal variation. Table 7 shows the maximum and minimum values of all ray and vessel parameters. Among 46 clones, average ray height (µm) ranged from 363.250 (clone 68) to 591.500 (clone 1); ray width (µm) ranged from 25.500 (clone 33) to 44.500 (clone 48); ray frequency from 10 (clone 44) to 23 (clone 86); vessel length (µm) from 352.65 (clone 62) to 546.59 (clone 45); vessel area (μm^2) from 12037 (clone 3) to 36470 (clone 62); vessel diameter from 114.250 (clone 3) to 176.00 (clone 85); and vessel frequency from 5 (clone 55 and clone 61) to 13 (clone 11).

On the basis of ray height all 46 clones were divided into 8 different subsets (figure 12). In the subset 1 ray height ranged from 363.25 to 495.00 µm and clones were: (clone 68< clone 56< clone 25< clone 54< clone 29< clone 88<

clone 58< clone 84< clone 83< clone 5< clone 86< clone 51< clone 89< clone 64< clone 35< clone 20< clone 47< clone 66< clone 85< clone 90< clone 53< clone 61< clone 3< clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44); in subset 2 it ranged from 380.25 to 517.50 μm and the clones were:(clone 56< clone 25< clone 54< clone 29< clone 88< clone 58< clone 84< clone 83< clone 5< clone 86< clone 51< clone 89< clone 64< clone 35< clone 20< clone 47< clone 66< clone 85< clone 90< clone 53< clone 61< clone 3< clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44< clone 62< clone 12< clone 69< clone 30< clone 11); in subset 3 it ranged from 388.75 to 521.00 μm and clones were: (clone 25< clone 54< clone 29< clone 88< clone 58< clone 84< clone 83< clone 5< clone 86< clone 51< clone 89< clone 64< clone 35< clone 20< clone 47< clone 66< clone 85< clone 90< clone 53< clone 61< clone 3< clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44< clone 62< clone 12< clone 69< clone 30< clone 11< clone 87< clone 72); in subset 4 it ranged from 398.30 to 533.00 μm and clones were: (clone 29< clone 88< clone 58< clone 84< clone 83< clone 5< clone 86< clone 51< clone 89< clone 64< clone 35< clone 20< clone 47< clone 66< clone 85< clone 90< clone 53< clone 61< clone 3< clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44< clone 62< clone 12< clone 69< clone 30< clone 11< clone 87< clone 72< clone 45); in subset 5 it ranged from 413.00 to 547.50 μm and clones were: (clone 84< clone 83< clone 5< clone 86< clone 51< clone 89< clone 64< clone 35< clone 20< clone 47< clone 66< clone 85< clone 90< clone 53< clone 61< clone 3< clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44< clone 62< clone 12< clone 69< clone 30< clone 11< clone 87< clone 72< clone 45< clone 48); in subset 6 it ranged from 420.25 to 555.60 μm and clones were: (clone 5< clone 86< clone 51< clone 89< clone 64< clone 35< clone 20< clone 47< clone 66< clone 85< clone 90< clone 53< clone 61< clone 3< clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44< clone 62<

clone 12< clone 69< clone 30< clone 11< clone 87< clone 72< clone 45< clone 48< clone 55); in subset 7 it ranged from 431.75 to 564.50 μm and clones were: (clone 35< clone 20< clone 47< clone 66< clone 85< clone 90< clone 53< clone 61< clone 3< clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44< clone 62< clone 12< clone 69< clone 30< clone 11< clone 87< clone 72< clone 45< clone 48< clone 55< clone 46); in subset 8 it ranged from and clones were: (clone 4< clone 60< clone 31< clone 74< clone 63< clone 73< clone 49< clone 33< clone 59< clone 41< clone 44< clone 62< clone 12< clone 69< clone 30< clone 11< clone 87< clone 72< clone 45< clone 48< clone 55< clone 46< clone 1).

On the basis of ray width all 46 clones were divided into 13 different subsets (figure 12). In the subset 1 ray width ranged from 25.20 to 33.25 μm and clones were: (clone 33< clone 58< clone 53< clone 25< clone 64< clone 54< clone 72< clone 45< clone 1< clone 5 < clone 55< clone 68< clone 84< clone 20< clone 90< clone 59< clone 56< clone 73< clone 86< clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69); in subset 2 it ranged from26.00 to 33.75 μm and clones were: (clone 53< clone 25< clone 64< clone 54< clone 72< clone 45< clone 1< clone 5 < clone 55< clone 68< clone 84< clone 20< clone 90< clone 59< clone 56< clone 73< clone 86< clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69< clone 83); in subset 3 it ranged from26.50 to 34.50 μm and clones were: (clone 25< clone 64< clone 54< clone 72< clone 45< clone 1< clone 5 < clone 55< clone 68< clone 84< clone 20< clone 90< clone 59< clone 56< clone 73< clone 86< clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47); in subset 4 it ranged from 26.75 to 34.75 μm and clones were: (clone 64< clone 54< clone 72< clone 45< clone 1< clone 5 < clone 55< clone 68< clone 84< clone 20< clone 90< clone 59< clone 56< clone 73< clone 86< clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85<

clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31); in subset 5 it ranged from 27.25 to 35.25 µm and clones were: (clone 54< clone 72< clone 45< clone 1< clone 5 < clone 55< clone 68< clone 84< clone 20< clone 90< clone 59< clone 56< clone 73< clone 86< clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31< clone 88); in subset 6 it ranged from 28.50 to 36.25 µm and clones were: (clone 73< clone 86< clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31< clone 88< clone 12); in subset 7 it ranged from 29.00 to 36.75 µm and clones were: (clone 90< clone 59< clone 56< clone 73< clone 86< clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31< clone 88< clone 12< clone 30); in subset 8 it ranged from 30.00 to 37.75 µm and clones were: (clone 66< clone 3< clone 87< clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31< clone 88< clone 12< clone 30< clone 44); in subset 9 it ranged from 31.50 to 39.00 µm and clones were: (clone 60< clone 61< clone 74< clone 89< clone 29< clone 11< clone 85< clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31< clone 88< clone 12< clone 30< clone 44< clone 4); in subset 10 it ranged from 32.00 to 39.50 µm and clones were: (clone 51< clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31< clone 88< clone 12< clone 30< clone 44< clone 4< clone 49); in subset 11 it ranged from 32.50 to 39.75 µm and clones were: (clone 41< clone 62< clone 63< clone 69< clone 83< clone 47< clone 31< clone 88< clone 12< clone 30< clone 44< clone 4< clone 49< clone 46); in subset 12 it ranged from 36.25 to 43.00 µm and clones were: (clone 12< clone 30< clone 44< clone 4< clone 49< clone 46< clone 35); in subset 13 it ranged from 37.75 to 44.50 µm and clones were: (clone 44< clone 4< clone 49< clone 46< clone 35< clone 48).

On the basis of ray frequency all 46 clones were divided into 18 different subsets (figure 12). In the subset 1 ray frequency ranged from 9.6 to 12.2 and clones were: (clone 44< clone 60< clone 46< clone 1< clone 4< clone 29< clone 35< clone 66< clone 45< clone 41< clone 63); in subset 2 it ranged from 10.6 to 13.0 and the clones were: (clone 60< clone 46< clone 1< clone 4< clone 29< clone 35< clone 66< clone 45< clone 41< clone 63< clone 30< clone 56< clone 62< clone 3< clone 69); in subset 3 it ranged from 11.0 to 13.6 and clones were: (clone 46< clone 1< clone 4< clone 29< clone 35< clone 66< clone 45< clone 41< clone 63< clone 30< clone 56< clone 62< clone 3< clone 69< clone 12< clone 53< clone 68< clone 48< clone 49< clone 84); in subset 4 it ranged from 11.4 to 13.8 and clones were: (clone 1< clone 4< clone 29< clone 35< clone 66< clone 45< clone 41< clone 63< clone 30< clone 56< clone 62< clone 3< clone 69< clone 12< clone 53< clone 68< clone 48< clone 49< clone 84< clone 11); in subset 5 it ranged from 11.8 to 14.2 and clones were: (clone 35< clone 66< clone 45< clone 41< clone 63< clone 30< clone 56< clone 62< clone 3< clone 69< clone 12< clone 53< clone 68< clone 48< clone 49< clone 84< clone 11< clone 64); in subset 6 it ranged from 12.0 to 14.6 and clones were: (clone 45< clone 41< clone 63< clone 30< clone 56< clone 62< clone 3< clone 69< clone 12< clone 53< clone 68< clone 48< clone 49< clone 84< clone 11< clone 64< clone 72< clone 85); in subset 7 it ranged from 12.4 to 15.0 and clones were: (clone 30< clone 56< clone 62< clone 3< clone 69< clone 12< clone 53< clone 68< clone 48< clone 49< clone 84< clone 11< clone 64< clone 72< clone 85< clone 83); in subset 8 it ranged from 12.8 to 15.4 and clones were: (clone 3< clone 69< clone 12< clone 53< clone 68< clone 48< clone 49< clone 84< clone 11< clone 64< clone 72< clone 85< clone 83< clone 90); in subset 9 it ranged from 13.0 to 15.6 and clones were: (clone 69< clone 12< clone 53< clone 68< clone 48< clone 49< clone 84< clone 11< clone 64< clone 72< clone 85< clone 83< clone 90< clone 73< clone 74); in subset 10 it ranged from 13.4 to 16.0 and clones were: (clone 12< clone 53< clone 68< clone 48< clone 49< clone 84< clone 11< clone 64< clone 72< clone 85< clone 83< clone 90< clone 73< clone 74< clone 51< clone 47); in subset 11 it ranged from 13.8 to 16.4 and clones were: (clone 11< clone

64< clone 72< clone 85< clone 83< clone 90< clone 73< clone 74< clone 51< clone 47< clone 58); in subset 12 it ranged from 14.2 to 16.8 and clones were: (clone 64< clone 72< clone 85< clone 83< clone 90< clone 73< clone 74< clone 51< clone 47< clone 58< clone 25< clone 87< clone 20< clone 54< clone 61); in subset 13 it ranged from 14.6 to 17.2 and clones were: (clone 72< clone 85< clone 83< clone 90< clone 73< clone 74< clone 51< clone 47< clone 58< clone 25< clone 87< clone 20< clone 54< clone 61< clone 55< clone 59); in subset 14 it ranged from 15.0 to 17.6 and clones were: (clone 83< clone 90< clone 73< clone 74< clone 51< clone 47< clone 58< clone 25< clone 87< clone 20< clone 54< clone 61< clone 55< clone 59< clone 5< clone 33); in subset 15 it ranged from 15.4 to 18.0 and clones were: (clone 90< clone 73< clone 74< clone 51< clone 47< clone 58< clone 25< clone 87< clone 20< clone 54< clone 61< clone 55< clone 59< clone 5< clone 33< clone 31); in subset 16 it ranged from 15.6 to 18.2 and clones were: (clone 73< clone 74< clone 51< clone 47< clone 58< clone 25< clone 87< clone 20< clone 54< clone 61< clone 55< clone 59< clone 5< clone 33< clone 31< clone 89); in subset 17 it ranged from 15.8 to 18.4 and clones were: (clone 51< clone 47< clone 58< clone 25< clone 87< clone 20< clone 54< clone 61< clone 55< clone 59< clone 5< clone 33< clone 31< clone 89< clone 88); in subset 18 it contains only one clone (clone 86) which had a ray frequency of 22.60.

On the basis of vessel area all 46 clones were divided into 7 different subsets (figure 13). In the subset 1 vessel area ranged from 12037.00 to 21999.67 μm^2 and clones were: (clone 3< clone 58< clone 49< clone 41< clone 89< clone 48< clone 54< clone 63< clone 74); in subset 2 it ranged from 17216.00 to 28295.60 μm^2 and the clones were: (clone 58< clone 49< clone 41< clone 89< clone 48< clone 54< clone 63< clone 74< clone 53< clone 1< clone 11< clone 64< clone 45< clone 4< clone 44< clone 83< clone 47< clone 72< clone 68< clone 35< clone 69< clone 88< clone 86< clone 46< clone 55< clone 25< clone 29< clone 5< clone 33< clone 56); in subset 3 it ranged from 19803.00 to 30215.89 μm^2 and clones were: (clone 41< clone 89< clone 48< clone 54< clone 63< clone 74< clone 53< clone 1< clone 11< clone 64< clone 45< clone 4< clone

44< clone 83< clone 47< clone 72< clone 68< clone 35< clone 69< clone 88< clone 86< clone 46< clone 55< clone 25< clone 29< clone 5< clone 33< clone 56< clone 90< clone 51< clone 84< clone 20); in subset 4 it ranged from 21045.69 to 32203.16 μm^2 and clones were: (clone 89< clone 48< clone 54< clone 63< clone 74< clone 53< clone 1< clone 11< clone 64< clone 45< clone 4< clone 44< clone 83< clone 47< clone 72< clone 68< clone 35< clone 69< clone 88< clone 86< clone 46< clone 55< clone 25< clone 29< clone 5< clone 33< clone 56< clone 90< clone 51< clone 84< clone 20< clone 66< clone 12< clone 73< clone 30); in subset 5 it ranged from 23006.20 to 34093.55 μm^2 and clones were: (clone 53< clone 1< clone 11< clone 64< clone 45< clone 4< clone 44< clone 83< clone 47< clone 72< clone 68< clone 35< clone 69< clone 88< clone 86< clone 46< clone 55< clone 25< clone 29< clone 5< clone 33< clone 56< clone 90< clone 51< clone 84< clone 20< clone 66< clone 12< clone 73< clone 30< clone 85< clone 61< clone 60< clone 59< clone 31); in subset 6 it ranged from 25039.28 to 35883.37 μm^2 and clones were: (clone 44< clone 83< clone 47< clone 72< clone 68< clone 35< clone 69< clone 88< clone 86< clone 46< clone 55< clone 25< clone 29< clone 5< clone 33< clone 56< clone 90< clone 51< clone 84< clone 20< clone 66< clone 12< clone 73< clone 30< clone 85< clone 61< clone 60< clone 59< clone 31< clone 87); in subset 7 it ranged from 25554.01 to 36470.20 and clones were: (clone 83< clone 47< clone 72< clone 68< clone 35< clone 69< clone 88< clone 86< clone 46< clone 55< clone 25< clone 29< clone 5< clone 33< clone 56< clone 90< clone 51< clone 84< clone 20< clone 66< clone 12< clone 73< clone 30< clone 85< clone 61< clone 60< clone 59< clone 31< clone 87< clone 62).

On the vessel diameter all 46 clones were divided into 19 different subsets (figure 13). In the subset 1 vessel diameter ranged from 114.25 to 146.50 μm^2 and clones were: (clone 3< clone 49< clone 58< clone 54< clone 41< clone 74< clone 45< clone 53< clone 89< clone 63< clone 64< clone 48< clone 1< clone 47< clone 44< clone 11< clone 72); in subset 2 it ranged from 116.00 to 148.00 μm^2 and the clones were: (clone 49< clone 58< clone 54< clone 41< clone 74< clone 45< clone 53< clone 89< clone 63< clone 64< clone 48< clone 1< clone 47<

clone 44< clone 11< clone 72< clone 68< clone 29); in subset 3 it ranged from 119.30 to 152.00 μm^2 and clones were: (clone 58< clone 54< clone 41< clone 74< clone 45< clone 53< clone 89< clone 63< clone 64< clone 48< clone 1< clone 47< clone 44< clone 11< clone 72< clone 68< clone 29< clone 4< clone 66< clone 35); in subset 4 it ranged from 129.75 to 161.76 μm^2 and clones were: (clone 54< clone 41< clone 74< clone 45< clone 53< clone 89< clone 63< clone 64< clone 48< clone 1< clone 47< clone 44< clone 11< clone 72< clone 68< clone 29< clone 4< clone 66< clone 35< clone 88< clone 5< clone 90< clone 69< clone 46< clone 56< clone 84< clone 33< clone 51< clone 86< clone 25< clone 20< clone 83); in subset 5 it ranged from 135.00 to 167.75 μm^2 and clones were: (clone 74< clone 45< clone 53< clone 89< clone 63< clone 64< clone 48< clone 1< clone 47< clone 44< clone 11< clone 72< clone 68< clone 29< clone 4< clone 66< clone 35< clone 88< clone 5< clone 90< clone 69< clone 46< clone 56< clone 84< clone 33< clone 51< clone 86< clone 25< clone 20< clone 83< clone 60< clone 12); in subset 6 it ranged from 136.25 to 169.60 μm^2 and clones were: (clone 63< clone 64< clone 48< clone 1< clone 47< clone 44< clone 11< clone 72< clone 68< clone 29< clone 4< clone 66< clone 35< clone 88< clone 5< clone 90< clone 69< clone 46< clone 56< clone 84< clone 33< clone 51< clone 86< clone 25< clone 20< clone 83< clone 60< clone 12< clone 59); in subset 7 it ranged from 138.25 to 171.50 μm^2 and clones were: (clone 64< clone 48< clone 1< clone 47< clone 44< clone 11< clone 72< clone 68< clone 29< clone 4< clone 66< clone 35< clone 88< clone 5< clone 90< clone 69< clone 46< clone 56< clone 84< clone 33< clone 51< clone 86< clone 25< clone 20< clone 83< clone 60< clone 12< clone 59< clone 30< clone 61< clone 73); in subset 8 it ranged from 140.00 to 173.50 μm^2 and clones were: (clone 48< clone 1< clone 47< clone 44< clone 11< clone 72< clone 68< clone 29< clone 4< clone 66< clone 35< clone 88< clone 5< clone 90< clone 69< clone 46< clone 56< clone 84< clone 33< clone 51< clone 86< clone 25< clone 20< clone 83< clone 60< clone 12< clone 59< clone 30< clone 61< clone 73< clone 87); in subset 9 it ranged from 143.00 to176.00 μm^2 and clones were: (clone 1< clone 47< clone 44< clone 11< clone 72< clone 68< clone 29< clone 4< clone 66< clone 35< clone 88< clone 5<

clone 90< clone 69< clone 46< clone 56< clone 84< clone 33< clone 51< clone 86< clone 25< clone 20< clone 83< clone 60< clone 12< clone 59< clone 30< clone 61< clone 73< clone 87< clone 31< clone 55< clone 62< clone 85).

On the basis of vessel frequency all 46 clones were divided into 14 different subsets (figure 13). In the subset 1 vessel frequency ranged from 5.2 to 7.4 and clones were: (clone 55< clone 61< clone 12< clone 29< clone 60< clone 83< clone 31< clone 45< clone 47< clone 68< clone 90< clone 5< clone 69< clone 86< clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73); in subset 2 it ranged from 5.4 to 7.6 and the clones were: (clone 12< clone 29< clone 60< clone 83< clone 31< clone 45< clone 47< clone 68< clone 90< clone 5< clone 69< clone 86< clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54); in subset 3 it ranged from 5.6 to 7.8 and clones were: (clone 60< clone 83< clone 31< clone 45< clone 47< clone 68< clone 90< clone 5< clone 69< clone 86< clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89); in subset 4 it ranged from 5.8 to 8.0 and clones were: (clone 31< clone 45< clone 47< clone 68< clone 90< clone 5< clone 69< clone 86< clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33); in subset 5 it ranged from 6.0 to 8.2 and clones were: (clone 45< clone 47< clone 68< clone 90< clone 5< clone 69< clone 86< clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33< clone 46); in subset 6 it ranged from 6.2 to 8.4 and clones were: (clone 5< clone 69< clone 86< clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33< clone 46< clone 4); in subset 7 it ranged from 6.4 to 8.6 and clones were: (clone 69< clone 86< clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33< clone 46< clone 4< clone 53< clone 58< clone 59); in subset 8 it ranged from

6.6 to 8.8 and clones were: (clone 41< clone 88< clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33< clone 46< clone 4< clone 53< clone 58< clone 59< clone 3< clone 48); in subset 9 it ranged from 6.8 to 9.0 and clones were: (clone 20< clone 51< clone 84< clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33< clone 46< clone 4< clone 53< clone 58< clone 59< clone 3< clone 48< clone 49< clone 64); in subset 10 it ranged from 7.0 to 9.2 and clones were: (clone 87< clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33< clone 46< clone 4< clone 53< clone 58< clone 59< clone 3< clone 48< clone 49< clone 64< clone 72< clone 85); in subset 11 it ranged from 7.2 to 9.4 and clones were: (clone 56< clone 35< clone 62< clone 63< clone 73< clone 54< clone 44< clone 89< clone 33< clone 46< clone 4< clone 53< clone 58< clone 59< clone 3< clone 48< clone 49< clone 64< clone 72< clone 85< clone 1< clone 25< clone 66); in subset 12 it ranged from 8.4 to 10.4 and clones were: (clone 4< clone 53< clone 58< clone 59< clone 3< clone 48< clone 49< clone 64< clone 72< clone 85< clone 1< clone 25< clone 66< clone 74); in subset 13 it ranged from 9.0 to 11.0 and clones were: (clone 49< clone 64< clone 72< clone 85< clone 1< clone 25< clone 66< clone 74< clone 30); in subset 14, only one clone was present which had a vessel frequency of 13.00.

On the basis of vessel length all 46 clones were divided into 14 different subsets. In the subset 1 vessel length (μm) ranged from 352.65 to 447.61 and clones were: (clone 62< clone 90< clone 64< clone 66< clone 83< clone 63< clone 85< clone 68< clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3); in subset 2 it ranged from 357.81 to 448.92 and the clones were: (clone 90< clone 64< clone 66< clone 83< clone 63< clone 85< clone 68< clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone

3< clone 87); in subset 3 it ranged from 368.63 to 461.85 and clones were: (clone 66< clone 83< clone 63< clone 85< clone 68< clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73); in subset 4 it ranged from 379.93 to 474.80 and clones were: (clone 83< clone 63< clone 85< clone 68< clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4); in subset 5 it ranged from 390.15 to 485.43 and clones were: (clone 63< clone 85< clone 68< clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47); in subset 6 it ranged from 390.83 to 487.22 and clones were: (clone 85< clone 68< clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35); in subset 7 it ranged from 393.78 to 489.54 and clones were: (clone 68< clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41); in subset 8 it ranged from 398.78 to 495.05 and clones were: (clone 30< clone 48< clone 59< clone 84< clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone

88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41< clone 46); in subset 9 it ranged from 408.74 to 501.87 and clones were: (clone 44< clone 61< clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41< clone 46< clone 33); in subset 10 it ranged from 411.27 to 506.07 and clones were: (clone 5< clone 56< clone 20< clone 31< clone 61< clone 5< clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41< clone 46< clone 33< clone 11); in subset 11 it ranged from 414.94 to 510.25 and clones were: (clone 56< clone 20< clone 31< clone 69< clone 86 < clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41< clone 46< clone 33< clone 11< clone 53); in subset 12 it ranged from 422.89 to 517.41 and clones were: (clone 25< clone 29< clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41< clone 46< clone 33< clone 11< clone 53< clone 51); in subset 13 it ranged from 434.42 to 525.97 and clones were: (clone 72< clone 88< clone 12< clone 3< clone 87< clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41< clone 46< clone 33< clone 11< clone 53< clone 51< clone 1); and in subset 14, it ranged from 457.40 to 546.59 and clones were (clone 49< clone 55< clone 58< clone 54< clone 73< clone 89< clone 74< clone 4< clone 47< clone 35< clone 60< clone 41< clone 46< clone 33< clone 11< clone 53< clone 51< clone 1< clone 45).

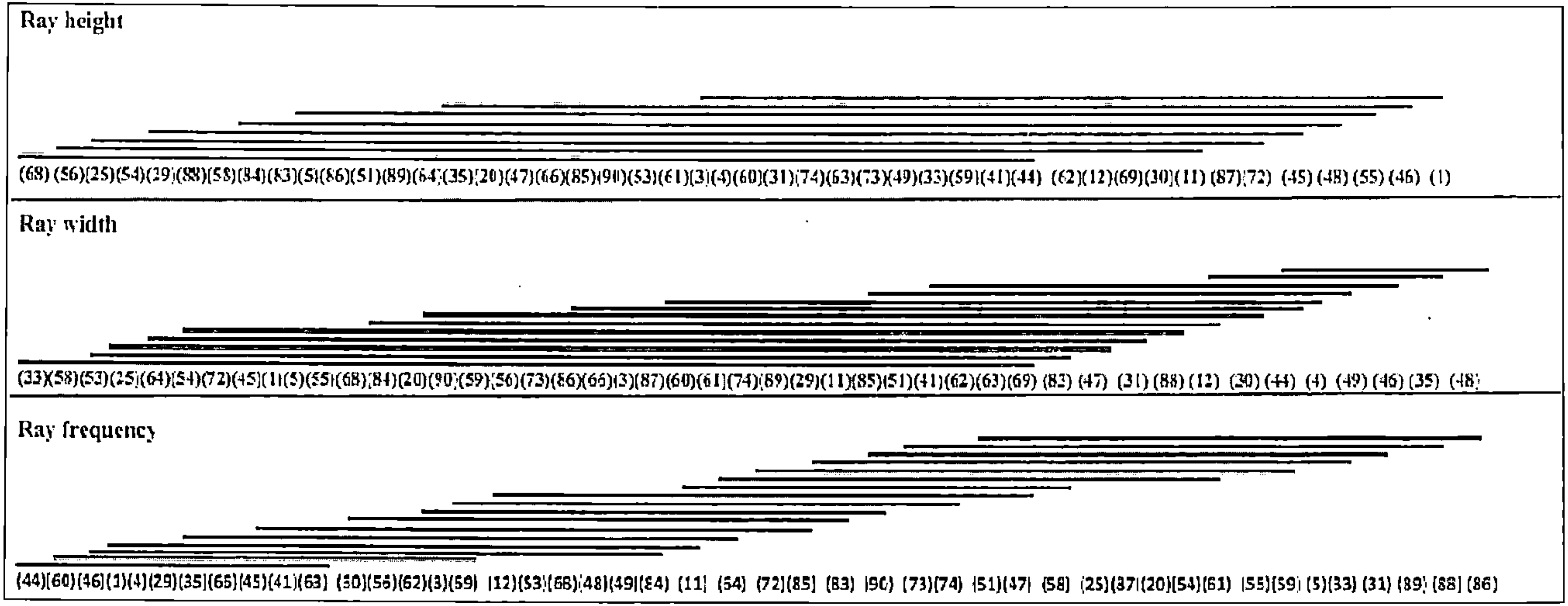


Fig.12. Bar diagram of all 47 trees on the basis of ray parameters- ray height, ray width and ray frequency

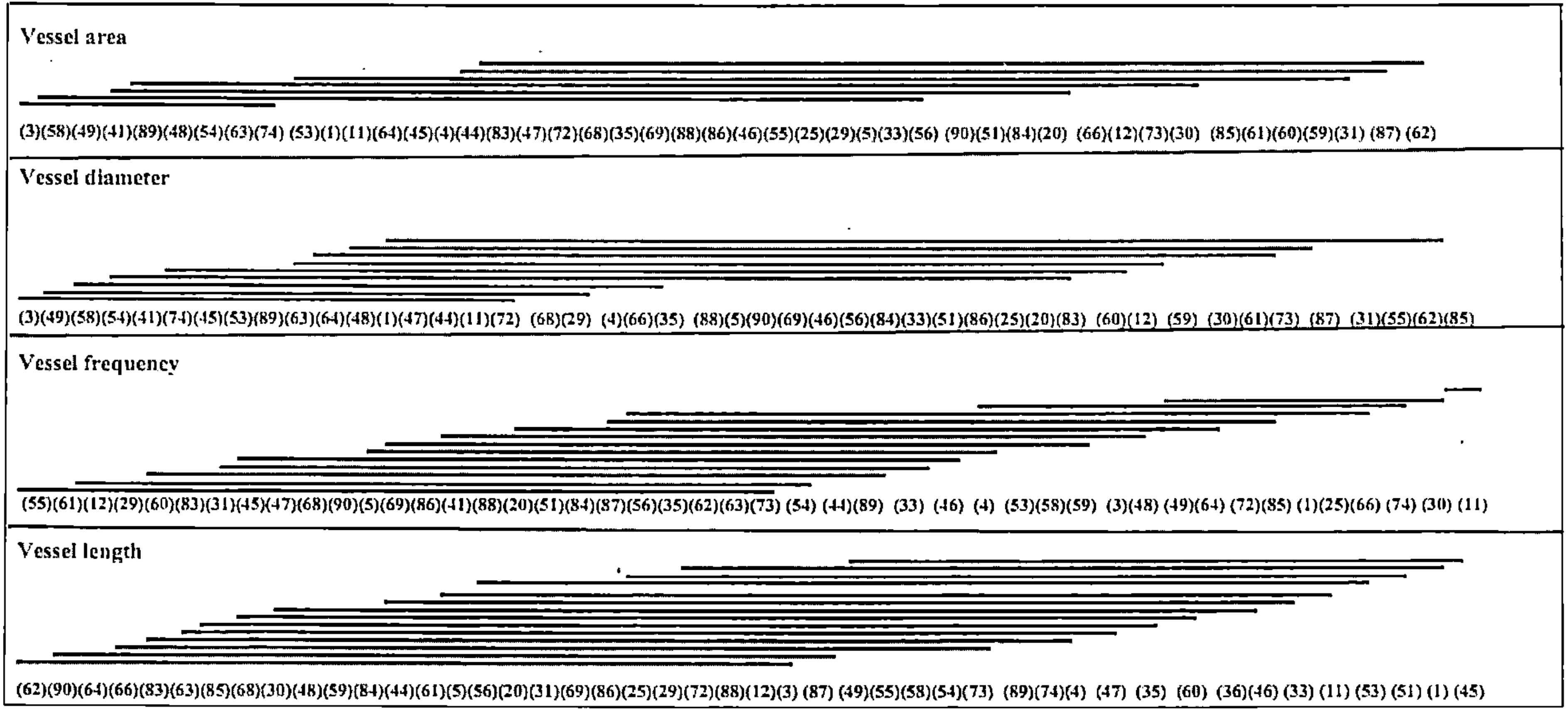


Fig.13. Bar diagram of all 47 trees on the basis of vessel parameters- vessel area, vessel diameter, vessel frequency and vessel length.

Table 7: Mean ray and vessel parameters of different clones

Clone number	Ray height(μm)	Ray width(μm)	Ray frequency (no/mm^2)	Vessel area (μm^2)	Vessel diameter (μm)	Vessel frequency (no/mm^2)	Vessel length (μm)
Clone 1	591.50 (39.75)	27.75 (2.48)	11 (0.51)	23059 (5064)	143.00 (16.64)	9 (0.81)	525.97 (26.12)
Clone 3	452.50 (63.25)	30.50 (2.11)	13 0.73)	12037 (846)	114.25 (4.91)	9 (0.37)	447.61 (28.54)
Clone 4	459.45 (22.49)	39.00 (1.99)	11 (0.40)	24391 (1427)	148.75 (4.95)	8 (0.75)	474.80 (41.75)
Clone 5	420.25 (35.10)	27.75 (2.32)	18 (0.68)	28085 (1513)	154.30 (6.46)	6 (0.66)	411.27 (18.16)
Clone 11	517.50 (74.35)	31.75 (3.27)	14 (0.97)	23113 (1029)	146.50 (2.63)	13 (1.45)	506.07 (36.21)
Clone 12	503.50 (60.16)	36.25 (3.51)	13 (0.87)	31829 (2102)	167.75 (5.86)	5 (0.51)	445.34 (25.85)
Clone 20	435.00 (43.36)	28.75 (1.90)	17 (1.28)	30216 (2762)	161.50 (12.76)	7 (0.37)	418.10 (20.84)
Clone 25	388.75 (20.47)	26.50 (1.74)	17 (1.81)	27774 (1472)	160.50 (8.59)	9 (0.68)	422.89 (28.42)
Clone 29	398.30 (19.22)	31.60 (3.80)	11 (0.51)	27981 (3398)	148.00 (8.45)	5 (0.24)	424.29 (32.97)
Clone 30	516.75 (40.04)	36.75 (4.45)	12 (0.68)	32203 (7037)	169.80 (19.81)	11 (0.55)	398.78 (21.86)
Clone 31	464.25 (40.21)	34.75 (2.35)	18 (0.89)	34094 (2809)	175.25 (10.39)	6 (0.66)	419.23 (20.50)
Clone 33	485.25 (19.27)	25.50 (1.09)	18 (1.21)	28217 (2568)	159.00 (8.820)	8 (0.45)	501.87 (20.17)
Clone 35	431.75 (19.74)	43.00 (2.97)	12 (0.37)	26013 (4021)	152.00 (15.03)	7 (0.24)	487.22 (20.39)
Clone 41	491.50 (29.95)	32.50 (1.31)	12 (0.80)	19803 (2783)	130.50 (8.91)	7 (0.51)	495.04 (27.31)
Clone 44	495.00 (35.82)	37.75 (1.99)	10 (0.51)	25039 (2873)	144.75 (8.23)	8 (0.58)	408.74 (29.02)
Clone 45	533.00 (8.50)	27.50 (1.85)	12 (0.63)	23470 (2132)	135.25 (7.43)	6 (0.45)	546.59 (37.22)
Clone 46	564.50 (47.94)	39.75 (3.25)	11 (0.71)	27458 (3521)	156.50 (12.40)	8 (0.66)	495.05 (27.09)
Clone 47	441.25 (9.21)	34.50 (1.88)	16 (0.95)	25718 (4496)	143.25 (13.19)	6 (1.22)	485.43 (32.19)
Clone 48	547.50 (61.81)	44.50 (2.00)	14 (0.51)	21409 (2333)	140.00 (7.41)	9 (0.58)	401.16 (18.25)
Clone 49	482.00 (17.63)	39.50 (2.52)	14 (0.51)	17526 (1181)	116.00 (4.83)	9 (0.71)	457.40 (22.07)

Clone 51	423.00 (31.30)	32.00 (1.84)	16 (0.58)	29047 (1551)	159.25 (4.38)	7 (0.37)	517.41 (28.12)
Clone 53	450.25 (71.10)	26.00 (1.55)	13 (0.68)	23006 (3209)	136.00 (8.01)	9 (0.93)	510.25 (37.45)
Clone 54	395.00 (21.80)	27.25 (1.55)	17 (0.86)	21416 (562)	129.75 (4.23)	8 (0.51)	460.15 (24.01)
Clone 55	555.60 (80.21)	27.75 (3.29)	17 (1.00)	27535 (2501)	175.40 (10.94)	5 (0.20)	457.86 (36.86)
Clone 56	380.25 (27.45)	29.50 (3.05)	12 (0.75)	28296 (4545)	156.50 (8.58)	7 (0.49)	414.94 (21.53)
Clone 58	410.25 (8.08)	25.50 (2.81)	16 (0.93)	17216 (1918)	119.30 (8.18)	9 (0.40)	459.32 (32.68)
Clone 59	486.00 (53.21)	29.25 (1.02)	17 (0.86)	33631 (7900)	169.60 (13.00)	9 (0.87)	402.36 (19.21)
Clone 60	462.25 (33.88)	31.50 (2.45)	11 (0.68)	33623 (4947)	167.25 (12.96)	6 (0.24)	489.54 (37.29)
Clone 61	452.25 (47.68)	31.50 (1.39)	17 (0.58)	33559 (3316)	171.00 (8.64)	5 (0.37)	409.09 (28.71)
Clone 62	501.75 (52.10)	32.50 (2.27)	12 (0.60)	36470 (3225)	176.00 (6.82)	7 (1.08)	352.65 (21.72)
Clone 63	478.75 (24.39)	33.00 (1.51)	12 (0.58)	21921 (1466)	136.25 (5.71)	7 (0.51)	390.15 (18.33)
Clone 64	425.00 (41.45)	26.75 (1.16)	14 (0.73)	23464 (3377)	138.25 (10.21)	9 (0.89)	360.17 (26.30)
Clone 66	441.75 (30.80)	30.00 (2.13)	12 (0.58)	31241 (2507)	149.00 (6.04)	9 (0.24)	368.63 (28.71)
Clone 68	363.25 (23.00)	27.75 (1.74)	13 (1.03)	25990 (3007)	147.00 (10.90)	6 (0.55)	393.78 (15.11)
Clone 69	513.75 (15.99)	33.25 (2.89)	13 (0.63)	26485 (1788)	155.75 (10.40)	6 (0.51)	419.89 (35.25)
Clone 72	521.00 (52.75)	27.25 (1.08)	15 (0.40)	25873 (744)	146.50 (4.02)	9 (0.73)	434.42 (16.32)
Clone 73	481.00 (34.25)	29.50 (0.64)	16 (0.40)	32195 (4004)	171.50 (10.45)	7 (0.24)	461.85 (35.80)
Clone 74	477.50 (10.02)	31.50 (1.87)	16 (0.40)	22000 (2247)	135.00 (8.79)	10 (0.51)	472.33 (32.66)
Clone 83	413.50 (11.56)	33.75 (1.63)	15 (0.45)	25554 (2224)	161.76 (8.81)	6 (0.51)	379.93 (16.33)
Clone 84	413.00 (27.61)	28.50 (1.70)	14 (0.51)	30025 (3750)	157.00 (11.11)	7 (0.37)	404.98 (31.55)
Clone 85	447.50 (26.63)	31.75 (2.52)	15 (0.51)	33520 (1116)	176.00 (4.55)	9 (0.58)	390.83 (19.49)
Clone 86	420.75 (22.67)	29.75 (0.73)	23 (1.29)	27211 (2700)	160.00 (8.70)	6 (0.51)	420.27 (26.21)

Clone 87	518.00 (36.30)	30.75 (2.42)	17 (0.40)	35883 (2800)	173.50 (4.44)	7 (0.55)	448.92 (28.63)
Clone 88	409.75 (26.24)	35.25 (1.45)	18 (0.98)	27164 (3090)	153.50 (6.70)	7 (1.03)	440.66 (38.02)
Clone 89	424.75 (18.71)	31.50 (1.91)	18 (0.73)	21046 (1240)	136.00 (7.17)	8 (0.66)	465.35 (37.96)
Clone 90	449.00 (27.34)	29.00 (1.55)	15 (0.93)	29036 (4613)	155.50 (12.73)	6 (0.45)	357.81 (19.01)
Total	**463.79 (6.12)**	**31.69 (0.42)**	**14 (0.20)**	**26779 (542)**	**151.72 (1.63)**	**7 (0.14)**	**440.36 (29.77)**

(Value in parenthesis is standard error of mean)

4.1.3. Chemical properties

4.1.3.1. Cellulose content

Student t-test was done for analysing the variation in cellulose content of the clones. Result showed that there is significant difference between clones in the case of cellulose content. Cellulose per cent among clones ranged from 41.66% for clone 56 to 58.86% for clone 1 (table 8). Average cellulose content of all the clones pooled together was 46.40 %. Standard error and standard deviation of mean is 4.083 and 0.60 respectively.

4.1.3.2. Lignin content

Percentage of lignin content (percentage) in 15 sorted clones showed significant difference between clones. Lignin per cent among clones ranged from 21.65% for clone 56 to 29.35% for clone 51 (table 8). Standard error and standard deviation of mean is 2.47 and 0.643 respectively.

Table 8: Cellulose and lignin content (percentage) of the top 15 clones

Sl. No.	Clone number	% of cellulose	% of lignin
1	Clone 1	58.86	29.3
2	Clone 5	46.22	26.43
3	Clone 11	53.36	28.71

4	Clone 30	51.37	28.54
5	Clone 41	43.53	24.59
6	Clone 44	45.87	27.45
7	Clone 45	47.28	22.56
8	Clone 46	46.81	27.53
9	Clone 47	42.83	24.86
10	Clone 49	47.98	23.76
11	Clone 51	42.95	29.35
12	Clone 56	41.66	21.65
13	Clone 60	41.89	28.31
14	Clone 63	51.37	26.64
15	Clone 68	43.18	24.76
	Total	**47.01**	**26.30**

4.3 INTER RELATIONSHIP BETWEEN WOOD PROPERTIES

Table 9 gives correlation coefficient between different wood properties of 46 clones. Specific gravity oven dry and specific gravity air dry were positively related. Fibre length was positively related to fibre cell wall thickness and was negatively related to fresh weight specific gravity and fibre lumen width. Fibre cell wall thickness was positively related to air dry specific gravity and negatively correlated to fibre lumen width. Fibre lumen width and fibre diameter were positively related to each other.

Among ratios and factors such as Runkel ratio, Slenderness ratio, Rigidity coefficient, shape factor, flexibility coefficient, first four parameters here positively related to fibre length, and negatively related to fibre diameter and fibre lumen width whereas flexibility coefficient showed inverse relationship with other factors. Fibre cell wall thickness was found to be positively related to Runkel ratio, rigidity coefficient and shape factor and negatively to the remaining parameters.

Table 9: Correlation coefficient for the interrelationship between wood properties in casuarina clones

	SGAD	SGFW	SGOD	FL	FW	FLW	FWT	RR	SR	RCO	FCO
SGAD	1										
SGFW	.125**	1									
SGOD	.485**	.129**	1								
FL	.114**	.018	.052	1							
FD	-.031	.022	.036	.062	1						
FLW	-.003	-.002	.014	.086*	.481**	1					
FWT	-.025	.035	.031	.036	.503**	-.157**	1				
RR	.042	.021	.073	-.006	-.232**	-.609**	.584**	1			
SR	.103**	-.002	.008	.599**	-.718**	-.302**	-.380**	.162**	1		
RCO	-.023	.021	.007	-.020	-.194**	-.538**	.738**	.869**	.118**	1	
FCO	.007	-.014	-.004	.078*	.234**	.955**	-.378**	-.690**	-.124**	-.614**	1
SF	.010	.030	.016	-.053	-.269**	-.871**	.505**	.829**	.162**	.785**	-.932**

** significant at 1% level; * significant at 5% level; others are non significant

SGAD – Specific gravity (air dry); SGFW – Specific gravity (fresh weight); SGOD – Specific gravity (oven dry)

FL – Fibre length; FW – Fibre width; FWT – Fibre wall thickness; FLW – Fibre lumen width; RR– Runkel ratio;

SR–Slenderness ratio; RCO– Rigidity coefficient; FCO–Flexibility coefficient; SF–Shape factor

For the selection of superior clones suitable for pulp and paper making whole clones were divided into clusters using hierarchical cluster analysis.

4.2. CLUSTER ANALYSIS ON THE PHYSICAL, ANATOMICAL AND GROWTH PARAMETERS

Hierarchical cluster analysis was conducted by using "Squared Euclidean Distance" for all clones considering physical, anatomical and growth parameters (see figure 14). The details of the clones and their growth parameters viz. DBH and heights are given in Appendix XXXIII. Dendrogram was prepared using average linkage (between groups). In the study, 46 clones were grouped in to 4 clusters at a rescaled distance of 5 units. The constituents of different clusters were given in Table 9. Cluster 1 was the largest cluster with 29 clones, cluster 2 contains 11 clones, cluster 3 contains 5 clones and cluster 4 contains only 1 clone. Cluster 1 was highly divergent from other clusters. Cluster 4 showed highest values for both DBH and height while cluster 3 showed lowest.

Table no 10: Total number of clones and name of clones in each cluster.

Cluster number	No of clones in cluster	Clone number
1	29	3,4,5,11,12,20,25,29,30,31,33,48,49,53,54,59,61,62,63, 64,66,69,72,74,83,84,86,87,89.
2	11	1,41,44,45,46,51,56,60,68,88,90.
3	5	35,55,58,73,85
4	1	47

4.2.1 Cluster-wise comparison of wood properties

Table 11 showed average specific gravity of clusters at three different conditions. Among four clusters, cluster 4 showed the highest values of specific gravity (air dry) and specific gravity (fresh weight). The highest value of specific gravity (oven dry) was for clone cluster 2. The lowest values of specific gravity (air dry), specific gravity (fresh weight) and specific gravity (oven dry) were for

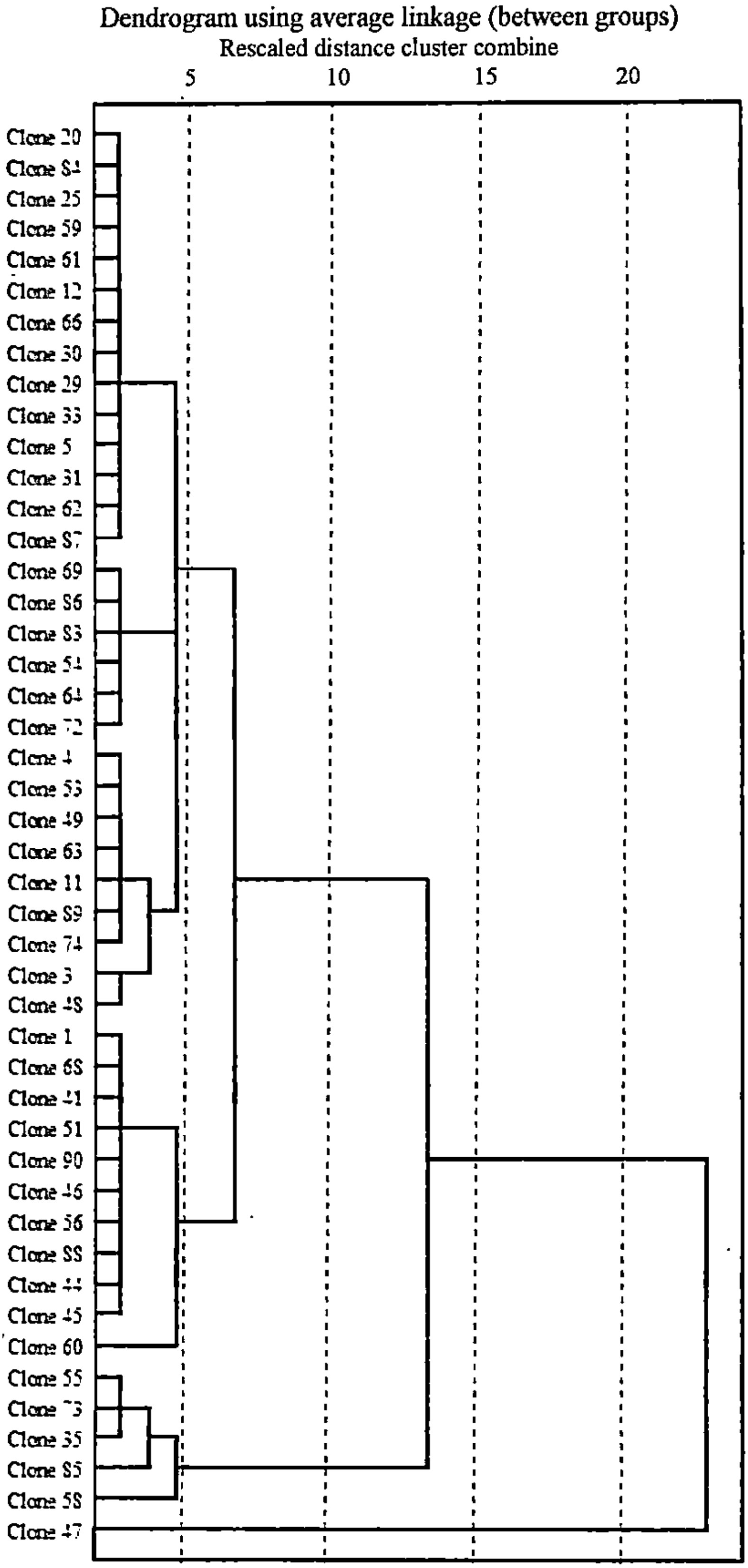


Fig.14. Dendrogram showing different clusters of clones

cluster 3, cluster 4 and cluster 3 respectively. The decreasing order of clusters for specific gravity (air dry) was cluster 4> cluster 1> cluster 2> cluster 3; for specific gravity (fresh weight) cluster 3> cluster 1> cluster 2> cluster 4; and for specific gravity (oven dry) cluster 2> cluster 4> cluster 1> cluster 3.

Cluster 4 showed the highest values for fibre length, fibre diameter and fibre lumen width whereas the highest value of fibre wall thickness was for cluster 2 (table 12). The decreasing order of clusters for fibre length was cluster 4> cluster 1> cluster 3> cluster 2; for fibre diameter cluster 4> cluster 2> cluster 3> cluster 1; for fibre lumen width cluster 4> cluster 1> cluster2> cluster 3; for fibre wall thickness cluster 2> cluster 4> cluster 3> cluster 1.

Table no 11: Mean values of specific gravity (air dry, fresh weight and oven dry) of four clusters

	Air dry specific gravity	**Fresh weight specific gravity**	**Oven dry specific gravity**
Cluster 1	0.795	1.168	0.742
Cluster 2	0.793	1.139	0.743
Cluster 3	0.783	1.173	0.734
Cluster 4	0.843	1.129	0.743

Table no 12: Mean values of fibre length (FL), fibre diameter (FD), fibre lumen width (FLW) and fibre wall thickness (FWT) of four clusters

	Fibre length (µm)	**Fibre diameter (µm)**	**Fibre lumen width (µm)**	**Fibre wall thickness (µm)**
Cluster 1	1470.22	25.10	9.79	7.68
Cluster 2	1417.74	25.33	9.75	7.98
Cluster 3	1419.03	25.15	9.44	7.75
Cluster 4	1484.00	26.62	11.36	7.77

Runkel ratio, slenderness ratio, rigidity coefficient, flexibility coefficient and shape factor was highest for cluster 3, cluster 1, cluster 2, cluster 4 and cluster 3 respectively (table 13). Cluster 4 showed the lowest values of all the ratios and factors except flexibility coefficient whereas it was lowest for cluster 3. The decreasing order of clusters for runkel ratio was cluster 3> cluster 1> cluster 2> cluster 4; for slenderness ratio was cluster 1> cluster 3> cluster 2> cluster 4; for rigidity coefficient was cluster 2> cluster 3> cluster 1> cluster 4; for flexibility coefficient was cluster 4> cluster 1> cluster 2> cluster 3; and for shape factor cluster3> cluster 1> cluster 2> cluster 4.

Table no 13: Mean values of Runkel ratio (RR), slenderness ratio (SLR), Rigidity coefficient (RIC), flexibility coefficient (FLC) and shape factor (SF) of four clusters

	Runkel ratio	**Slenderness ratio**	**Rigidity coefficient**	**Flexibility coefficient**	**Shape factor**
Cluster 1	1.902	120.32	61.60	76.68	0.739
Cluster 2	1.893	114.66	63.25	76.20	0.738
Cluster 3	1.948	115.82	62.28	73.55	0.753
Cluster 4	1.549	112.60	59.06	84.03	0.695

Table 14 shows average values of ray and vessel dimensions in each cluster. Both vessel area and vessel diameter was highest for cluster 2. Cluster 4 showed the highest values of both vessel frequency and vessel length. The lowest values of vessel area and vessel diameter were measured in cluster 4. Both cluster 1 and cluster 3 had the lowest value of vessel frequency. Vessel length was lowest for cluster 1. Both ray width and ray frequency was highest for cluster 4 and ray height for cluster 2. The lowest ray height, ray width and ray frequency was measured in cluster 4, cluster 3 and cluster 2 respectively.

Table no 14: Mean values of ray and vessel parameters (VL-vessel length, RH-ray height, RW-ray width, RF-ray frequency, VA-vessel area, VD-vessel diameter and VF-vessel frequency) of four clusters

	Ray height (μm)	**Ray width (μm)**	**Ray frequency (no/mm^2)**	**Vessel length (μm)**	**Vessel area (μm^2)**	**Vessel diameter (μm)**	**Vessel frequency (no/mm^2)**
Cluster 1	462.21	31.57	15	428.56	26815.78	151.48	7
Cluster 2	469.36	31.84	13	462.32	26544.17	149.91	8
Cluster 3	465.22	31.50	15	451.42	27296.06	158.84	7
Cluster 4	441.25	34.50	16	481.43	25718.07	143.25	9

DISCUSSION

DISCUSSION

The clones taken for present study were obtained through Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore. They established trial plantation at Puducherry in 2003 using the bulked seeds obtained from the first generation SSO at Sadivayal (Karunya campus), Coimbatore. A total of 87 clones and 3 seedlots were selected. The clone was selected based on individual tree superiority for height, diameter at breast height and straightness of stem through index selection method. These selected clones were tested in three different locations namely, (1) Mayiladumparai, near Kulithalai, Tamil Nadu (Inland, red soil), (2) Moorthypuram, near Karur, Tamil Nadu (Inland, sodic soil) and (3) Sirugramam, near Cuddalore, Tamil Nadu (Casuarina growing zone). Height, diameter at breast height, volume index and straightness were measured for these clones. Based on analysis and overall ranking with respect to above mentioned parameters, three clones, Clone 47, clone 60 and clone 56 were shortlisted for consideration of release. Similar to this, the present study also tried to rank 46 clones obtained from Moothypalayam, Karur district, based on its anatomical, physical and pulp and paper qualities.

The results obtained from the study titled "Wood property variation in selected clones of *Casuarina equisetifolia* L. grown in Karur district, Tamil Nadu for pulp and paper making." were discussed under the following topics.

1. Inter and intra-clonal variation in wood properties of casuarina clones

2. Suitability of casuarina clones for pulp and paper making

5.1. INTER AND INTRA CLONAL VARIATION (AXIAL VARIATION) IN WOOD PROPERTIES OF CASUARINA CLONES

5. 1.1Physical properties

5.1.1.1 Specific gravity

Of all the wood properties, specific gravity (density) is the most important and the most widely studied characteristic which correlates with numerous morphological, mechanical, physiological, and ecological properties (Jerome *et al.*, 2006). A lot of studies on wood specific gravity have been conducted previously for finding variation within and between species. The present study is also discussing three specific gravity measures such as air dry specific gravity, fresh weight specific gravity and oven dry specific gravity. The study revealed that three specific gravity measures have significant variation between clones. Furthermore both specific gravity (fresh) and specific gravity (air dry) showed significant difference along axial directions within clones.

According to Zobel and Talbert (1984), basic density varies greatly within and between species, being strongly influenced by geographic location, site fertility, age and genetics. So geographic location is one of the reasons for within and between tree variations of specific gravity. Usually clones exhibit a strong affinity to the site of their origin. When the different clones of the same species were planted in a new site, some of the clones performed well in terms of superior growth, anatomical, physical and chemical properties while some did not perform well in these respects. This was because of the resemblance of site conditions of these clones with their site of their origin. For instance, as the part of clonal testing program on eucalyptus spp., a number of clones were planted in different sites (Kulkarni, 2002). Among these clones, clone 1, 10 and 130 adapted well in black soils (normal, alkaline and saline), forever clone 10 did not tolerate saline sandy soils which lead to high mortality. However, in the same plot clone 411 and 413 were performing well with high productivity and survival. So the difference in wood growth, physical, anatomical and chemical properties of clones even though growing in the same stand will depend on similarity of site of their origin and their growing site. This is applicable in the case of casuarina clones also which resulted in inter-clonal variation of wood properties.

Specific gravity is a complex feature which is 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). A study on *Eucalyptus spp.* found that density differences in eucalypts are largely driven by changes in cell wall thickness and vessel size (Downes *et al.,* 1997). This study found significant variation in vessel size, vessel and ray frequency, cellulose and lignin content, cell wall thickness. These variations contribute to between and within tree variation of specific gravity of clones. Wood density of four year old clones of *E. grandis* grown in Columbia showed variation between sites and between clones within sites. Density varied from 319 kg m^{-3} to 514 kg m^{-3} between clones and from 391 kg m^{-3} to 434 kg m^{-3} between sites.

In the present study casuarina clones showed a high density at the base, a decrease for some distance up the tree, followed by an increase towards the axial directions. Species such as *Swietenia macrophylla* (Briscoe *et al.*, 1963), *Liriodendron tulipifera* (Taylor, 1968), *Populus tremuloides* (Einsphahr *et al.*, 1972; Yanchuk *et al.*, 1983) and *Liquidambar styraciflua* (Webb, 1964) showed the same pattern of variation of specific gravity. A lot of researchers studied specific gravity variation at different intervals along the axial direction of the tree. Raymond and MacDonald (1998) studied specific gravity of three *Eucalyptus spp.* (*E. globulus, E. nitens* and *E. regnans*) at fixed heights showed a linear increase in density above 10% height, sometimes accompanied by an initial decrease between the base of the tree and 10%. Samples taken at fixed heights showed that the initial decrease invariably occurred in the first 0.5 m above the ground. Many studies on density of wood of *Eucalyptus spp.* (Beadle *et al.*, 1996 on *E. globulus*; Taylor, 1973, Barrichelo *et al.*, 1983 and Vital and della Lucia, 1987 on *E. grandis*; Lausberg *et al.*, 1995, Purnell, 1988, Beadle *et al.*, 1996 on *E. nitens*; Frederick *et al.*, 1982 and Raymond *et al.*, 1997 on *E. regnans*) showed similar pattern of variation as shown in casuarina clones. Okkonen *et al* (1972) studied relationship of wood specific gravity to height in 28 commercially important timber species. In the 17 species studied the specific gravity decreased with an increase in height, in five it decreased, in three it decreased for a time and then increased, and in three no specific change was observed. Frederick *et al.* (1982) studies *Eucalyptus regnans* growing in the New Zealand and found a decrease in density from the base to 1.4 m (first sampling height) followed by a linear increase. Purnell (1988) found a similar pattern with density decreasing between the base and first sampling height at 2.4 m, followed by a linear increase from 2.4 m to 12 m in 11-year-old *Eucalyptus nitens* in South Africa.

5.1.2 Anatomical properties

The study revealed that all the anatomical properties except fibre lumen width showed significant difference between clones. Within clone axial variation was highly significant for all the anatomical properties studied. Previously, a substantial number of works have been done in different species to understand between and within clone variations. Similar to the present study, previously many researchers namely Phelps *et al.*, (1982), Koubaa *et al.*, (1998), Rao *et al.*, (2002) and Pande and Singh (2005) studied anatomical variations in wood elements within and among clones (*Populus spp., Eucalyptus spp. and Dalbergia spp.*) to assess its wood quality.

5.1.2.1Fibre morphology

Fibre length, fibre diameter, fibre lumen diameter and fibre cell wall thickness were the parameters analysed under this topic. All these parameters showed significant differences due to clone effect. Similar to the present study, significant variation for fiber properties among the clones of *Eucalyptus tereticornis* was reported by Shashikala and Rao (2005). Chauhan *et al.* (2001) reported that inter clonal differences were significant in *Populus deltoides* for fibre dimensions. Various studies on Poplars by Holt and Murphey (1978), Murphey *et al.* (1979), Yanchuk *et al.* (1984), Bendtson and Senft (1986), Koubaa *et al.* (1998) and DeBell *et al.* (1998) revealed significant clonal and axial variation in fibre length. Gautam *et al.* (2008), showed inter-ramets variation in wood traits of micro propagated L-34 clone plantation of *Populus deltoides*. Further, Pande and Singh (2005) reported non-significant inter-ramet variations among the 4 years old clonal ramets of *Eucalyptus tereticornis*. Ramirez *et al.* (2009) studied clonal variations in fiber properties among 7-year-old *Eucalyptus globules* 14 clones. They observed a narrow range of variation for fiber wall thickness, fiber diameter and lumen diameter. Among the clones, significant differences were observed for fiber diameter. Fibre wall thickness remained constant for all trees across clones. Hans *et al.* (1972) observed a marked variation among trees for fiber length in *Eucalyptus grandis*.

Axial pattern of fibre dimension variation is relatively less consistent than in the radial direction (Barrichelo *et al.* 1983). In the present study casuariana clones showed significant axial variation in fibre dimensions. But the mean variation was very less. Fibre length, fibre diameter and fibre lumen width exhibited the same pattern of variation. All the three parameters showed small initial decreases from base to middle followed by increase towards the top. But cell wall thickness showed increasing trend from base to top. A study by Raymond *et al.* (1997) on *E. regnans* showed small decrease in fibre length between the base of the tree and 10% total height, followed by increase up to 20% of total height and decrease thereafter. This study is in agreement with the present study.

In contrast to the present study many other researchers reported different patterns of axial variations in different species. Rao *et al.* (2003)

reported significant axial variations in fiber length of *Eucalyptus tereticornis* clones with no definite trend. Webb (1964) reported that fiber length showed a constant decrease in *Liquidambar styraciflua* with increased height and was largest at the stump and logs from base positions have relatively higher long fibre content than log from top positions. Chauhan *et al.* (2001) reported that the fiber length reached the maximum at 25% of tree height showing a decreasing trend upwards. Valente *et al* (1992) observed decrease in fibre length with height in eight year old to 12-year-old *E.globulus* sampled at four heights. In *Acacia melanoxylon* fiber length decreased from bottom to the top of the tree and wall thickness had no specific variation pattern (Tavares *et al.*, 2010). Fibre length varied from an average of 1.51 mm and 1.42 mm to 1.34 mm at 5%, 35% and 65% of total tree height respectively. This type of pattern was also described by Iqbal and Ghouse (1983) for *Acacia nilotica* with a variation of 1.12 mm in the base, 1.16 mm in the middle and 0.986 mm at the top of the tree. Members of the genus Picea showed only a slight change with height (Nylinder and Hagglund, 1954; Jeffers, 1959; Stern, 1963; Provin 1971; Taylor *et al.*, 1982). Some conifers species, such as *Chamaecyparis obtuse* (Hirai, 1958) or *Tsuga heterophylla* (krahmer) have longer tracheids at the base of the tree and shorter ones near the top. In the case of cell wall thickness, it increased from base to top in the present study. In contrast to this, for *Eucalyptus globulus*, the fiber wall thickness decreased from the base to the top with 7.3 µm, 6.4 µm, 6.1 µm, 5.5 µm, and 5.4 µm at 5%, 15%, 35%, 55% and 75% of tree height (Quilho *et al.*, 2000).

A study of Ridoutt and Sands (1993) have shown that the size of the cambial initials in *E. globulus*, and subsequent cell enlargement and wall thickening, determine fibre cell morphology. They observed a positive within tree relationship between the decrease in fibre length with height and the concomitant decrease in the length and width of the fusiform initials in the vascular cambium. Dimensions of the cambial fusiform initials generally increased from stem base to a certain tree height and then decreased towards the uppermost part of the tree. Both the length of the cambial initials and the amount of elongation the initial undergoes determine the resultant length of mature fibres. Variation in the length of cambial initials accounted for 62% of the variation in mature fibre length with height. A sharp decrease in the length of fusiform initials at 2.5 % height was associated with a similar decrease in mature fibre length at 2.5% height. Fibre length increased from 2.5% to 5% tree height together with an increase in fusiform initial length. As in the case of *Eucalyptus spp.* variations in the length and width of the fusiform initials determine the longitudinal variations of fibre morphology of casuarina clones. Fibre length also depends on the degree of intrusive growth (Ghouse & Siddiqui, 1976; Khan & Siddiqui, 2007; Lev-Yadun, 2010) and on maturation and outlines of surrounding cells (Jura- Morawiec, 2008), which can justify the axial variation in vessel element length and secondary phloem fibres.

In general, axial variations in fibre width, fibre lumen width and fibre wall thickness is very less compared to fibre length. There are no comparable studies concerning the axial variation of the secondary phloem fibre width and wall thickness. Width and fibre wall thickness could be affected by alterations of hormonal content, i.e. a longitudinal decrease in auxin concentration was responsible for fibre enlargement (Lev-Yadun & Aloni, 1991). According to Antonova *et al.* (2005), concentration of ascorbic acid, high in early stage of xylem development in growing season correlate positively with radial enlargement of tracheids. Ascorbic acid and its oxidised form- dehydra ascorbic acid accelerate cell division and cell enlargement which results in radial increase in cell dimensions. However, information is still lacking on hormone interaction during cambial development and on genetic regulation of secondary vascular growth and cell differentiation (Elo *et al.*, 2009; Lev-Yadun, 2010; Spicer & Groover, 2010).

In hardwoods the fibre length pattern vary but the most common pattern is to have slightly longer fibres at the base than in the top or for the fibres to be essentially of the same length at all height. Usually for hardwoods, even though the pattern is evident, their magnitude is generally small and the differences in both specific gravity and fibre length with height do not have a major effect on the utilization of the wood.

5.1.2.2 Vessel morphology

Vessels are unique features of hardwoods which are important cellular constituents designed to perform the function of conduction of water and mineral nutrients in the living trees (Panshin and de Zeeuw, 1980; Carlquist, 1988). The present study showed significant inter-clonal variation among clones. As mentioned earlier, similarity of site to their origin of site and genetic factors are the driving factor for the variations in vessel morphology among clones. Similar to the present study Pande and Singh (2009) observed significant inter clonal variations in *Eucalyptus tereticornis* in vessel element dimensions viz. length and diameter. Significant variations in vessel frequency, vessel element diameter and vessel length was reported by Shashikala and Rao (2005) among the clones of *Eucalyptus tereticornis*. Similarly Ramirez *et al.* (2009) reported wide range of variation in 7-year-old *Eucalyptus globules* clones for vessel frequency, vessel area and vessel coverage among the clones. Leal *et al.* (2003) studied clonal and site variation of vessels in 7-year-old *Eucalyptus globulus* and found that vessel characteristics varied across clones on each sites; e.g. at Nogueiroes vessel area ranged from 6677 μm^2 to 10670 μm^2, vessel frequency from 9.2 to 13.4 vessels /mm^2 and vessel coverage from 7.6% to 12.7%. Significant differences were found for vessel coverage with site and clone accounting respectively for 67% and 30% of the total variation. Significant intra and inter ramet variation in vessel dimensions of micro propagated L-34 clone plantation of *Populus deltoides* was reported by Gautam *et al.* (2008).

5.1.2.3Ray morphology

Taylor (1973) in his study on *E. grandis* at different sampling heights found that ray and longitudinal parenchyma volume remained constant with height, and between trees variation was minor. Huda *et al.* (2012) reported significant difference in ray proportion among poplar clone. The present study also revealed significant variation in ray length, ray width and ray frequency. Lack of literature related to inter clonal variation in ray morphology limited the discussion of the same.

5.1.3 Chemical properties-Cellulose and lignin content

Parthiban *et al.* (2011) studied pulpwood characterization of 25 short rotation casuarina hybrid clones. Clones showed non-significant variation between clones. The chemical properties of clones indicated that maximum holocellulose content was observed in CJ-14 and minimum in CJ-25. The lignin content ranged between 24.2 and 27.8 per cent. Klas *et al.* (2010) compared the chemical composition of wood fibres and fibre surfaces of several eucalypt species and hybrids originating from various growth sites in South Africa. They found that *E. grandis* clone had 48% cellulose content, followed by *E. grandis* and the two hybrids, *E. grandis* × nitens and *E. grandis* × *camaldulensis* with about 46%. The lowest cellulose content was found in *E. dunnii* with 44%. Lignin content followed the same trend as cellulose; the *E. grandis* clone had the largest amount of lignin (21%) and *E. dunnii* had the lowest (13%). The maximum variation in bulk lignin content between the species was 8%. Vennila *et al.* (2011) studied twenty seven clones in three Eucalyptus species viz., *Eucalyptus camaldulensis, Eucalyptus tereticornis* and *E. urophylla* were subjected for pulp quality analysis. All clones showed moderate to high range of physical properties. The proximate analysis indicated the variability among the clones. The lignin content was moderate (23 – 27.8) for all the clones. The clones differed significantly for holo-cellulose, which ranged between 68.5-74.6. Tullus *et al.* (2009) studied relationships between cellulose, lignin and nutrients in the stemwood of hybrid aspen in Estonian plantations and found that wood chemical components have significant differences in cellulose and lignin concentrations among the hybrid aspen clones. The clones of hybrid aspen in Estonian experiments had much lower lignin (10.5-11.7%) and higher cellulose content (57-60.2%) in stem wood, which recommends hybrid aspen as a promising source for energy, paper or solid wood production. In the present study showed significant inter clonal variation in cellulose and lignin content.

5.2. Suitability of casuarina clones for pulp and paper making

5.2.1 Physical properties

5.2.1.1 Specific gravity

Specific gravity simply explains the amount of wood substance present per unit volume. It 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). It is realized from many other studies (Dinwoodie, 1966; Watson and Hodder, 1954; Watson *et al.*, 1952) that wood density is a major factor in the ultimate performance of fiber as a raw material for pulp.

Wimmer *et al.* (2002) who studied the relationship between whole tree properties, and pulp and handsheet properties in *E. globulus* clones and found that wood density was a strong predictor of most handsheet properties. Many research works on wood property-pulp and paper property reported 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). According to Ramirez *et al* (2009), high densities produce bulkier, more porous sheets with lower tensile and burst index and high tear index. Lower density woods mainly produce denser sheets with high tensile strength. In an another study, Einspahr *et al.* (1969) found that handsheets made from high specific gravity trees results in open textured, bulky sheets of lower apparent density. 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). Many researchers put forward specific values or ranges of specific gravity (or density) applicable for specific purposes. According to Chittenden and palmer (1990), wood having density more than 600 kg/m^3 was less preferable for paper making. Ikemori *et al.* (1986) suggested that wood density which is in the range of 480-570 kg/m^3 is ideal for paper and pulp making. In the present study, it was found that all the clones had density higher than 600 kg/m^3 which indicates that the clones are on the higher side of density range suitable for pulping. It is well known that within the range higher values are preferred on account of higher pulp yield.

5.2.2 Anatomical properties

5.2.2.1 Fibre morphology

The relationship between wood pulp fibre morphology and paper properties has been extensively studied over the years. The properties of pulp and paper products highly depend on the dimensions of the fibres forming the products and on the ability of these fibres to bind to each other in a fibre network. It has become increasingly important to identify key fibre dimensions that can be used to predict ultimate pulp and papermaking performance in industrial level. According to Downes *et al.* (1997), fibre length, fibre diameter and wall thickness are the most important fibre dimensions considered for pulp and paper manufacture. Monteoliva *et al.* (2005) reported that fiber anatomical properties have a major influence on the quality of pulp and paper products. Knowledge of variation of fibre morphology is essential for obtaining improved wood quality, for better clone selection and for various end uses such as pulp and paper making. The significant variation in morphological properties within sites and clones of seven poplar hybrid clones indicates good opportunities for selecting the most performing clones in terms of anatomical properties, both for breeding and for processing for specific end uses (Huda *et al.*, 2011).

Species having higher fiber length is preferred for pulp and paper production because a better fiber network is achieved, resulting in higher paper strength (Dadswell and Watson, 1962; Wangaard, 1962; Dinwoodie, 1966; Wardrop, 1969; Scurfield, 1976; Amidon, 1981; Seth, 1988). Horn (1978) reports that increase in raw material fiber length enhance the tearing strength of hardwood pulps. As the number of binding points for a single fibre increases with its length, the tensile and tear strength of paper are both found to be increased with fibre length in weakly bonded sheets, whereas in a well-bonded sheet, the tear and tensile strength depend less on fibre length (Seth and Page, 1988; Niskanen, 1998). Horn (1974) described the fibre morphology of 12 Indian species and stated that no relation could be found between fibre characteristics and strength properties of paper. Wide variation existed within species for fibre length which is considered to be an important factor for tearing strength and fibre thickness/fibre diameter ratio which is associated with breaking strength and burst factor of wood pulp. Guha and Nadan (1963) reported that *Casuarina equisetifolia* have high pulp yield with good satisfactory strength properties. An increase in fiber length resulted in increased pulp yield, tear index, bending stiffness, freeness, burst strength and permanence, whereas reduction in fiber length reduces 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). Loss of fiber strength has little effect on 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 generally, both short and long fibres are required to furnish good grade paper whereas to certain extent the quality of paper is decided by the quality of its fibres.

Variation in fibre cross-sectional dimensions strongly affects pulp and paper properties (Amidon, 1981). Studies of Pliura *et al.* (2007) and Huda *et al.* (2011) on poplar hybrids found that fiber wall thickness was positively correlated to wood density. At the cellular level, increased cavitation resistance and stem mechanical strength were associated with thicker cell walls (Jacobsen *et al.*, 2005). According to Karlsson (2006), fibre width is needed to be considered for pulp and paper making. He suggested that narrow fiber width is desirable for pulp and paper applications because it results in smoother paper and more uniform formation. Pulkkinen *et al.* (2008) studied the use of fibre wall thickness data to predict handsheet properties of eucalyptus pulp fibres and revealed that fibre wall thickness distribution was found to be the major contributor of handsheet properties studied, such as tensile strength, sheet density and air resistance. He concluded that fibres with low wall thickness and narrow fibre wall thickness distribution had higher strength properties, density of the handsheets and air resistance. Fiber length and fiber width had no significant effect on measured properties. He reported that the thick-walled fibres with wide wall thickness distribution have a wide stress distribution with a different amount of fibre shrinkage between adjacent fibres, resulting in a higher change in sheet dimensions and producing relatively loose fibre network. Thus the fibre network with heterogeneous shrinkage causes lower strength values of the fibre network and decreased activation of the sheet. Fibres with low density are thin-walled and produce dense sheets with improved bonding and fibre segment activation that resulted in higher tensile index values. Cell wall thickness governs fibre flexibility. Thick walled fibre adversely affects the bursting strength, tensile strength and folding endurance of paper. The paper manufactured from thick walled fibres was bulky, coarse surfaced, and containing a large amount of void volume. But the paper from the thin walled fibres was dense and well formed. Fibre lumen width affects the beating of pulp. Larger the fibre lumen better will be the beating of pulp because of the penetration of the liquids into the fibre lumen.

In the present study, the higher fibre length (1452.41µm) of casuarina clones as compared to eucalyptus species and some other hardwoods makes it suitable for pulp and paper making. Longer fibre will impart greater network and tensile strength for pulp. Higher lumen width also preferable for pulp and paper making in the case of casuarina clones. However the higher fibre wall thickness of casuarina clones will adversely affects pulp and paper quality. Higher fibre wall thickness will produce bulky and coarse surfaced paper.

5.2.2.2 Vessel morphology

The size and structure of anatomical elements that influences wood properties and its variation can be used to improve the quality of end products. Despite extensive research about relationships between fibre morphology and pulping quality, only a few studies have concentrated on vessel sizes and their variability. Vessel diameter and vessel frequency in species are taken as indices for wood quality assessment especially for pulping and paper making. During the papermaking process, high vessel coverage results in higher penetration of pulping chemicals into the wood and increases bulk. It also reduces surface quality of the paper, because vessel elements may pick out from the paper surface during the printing process, leaving ink-free spots on the printed page. (Ramirez *et al.* 2009). Chen and Evans (2004) found that the nature and properties of vessel are important in impregnation of chemical preservatives, drying, gluing, painting, cutting and other processes. Previously mentioned study of Lei *et al* (1997) also came with same opinion. According to him fast-grown *A. rubra* trees produce wood with slightly wider vessels, which is unfavourable for paper making and solid-wood products; large vessel diameter leads to problems in refining and printing processes and difficulties in the finishing of solid wood.

In the present study, vessel diameter of casuarina clones (151 μm) was within the range of other hardwoods. Vessel area and vessel frequency was much lower than other hardwoods like *Eucalyptus spp.* So casuarina clones are preferable to other hardwoods with respect to vessel morphology for pulp and paper making.

*5.2.2c **Ray morphology***

The ray and parenchyma cells themselves are thin-walled and very short and contribute little to the strength properties of paper, although they provide smoother sheet. Just as for vessels, there is interest in trees with a lesser amount of ray cells because of their variability and adverse effect upon specific gravity, yield of paper, and strength of paper (Zobel, 1989). So in the present study relatively higher ray frequency of casuarina clones has adverse effects on pulp and paper quality.

*5.2.2d **Ratios and factors***

Ratios, indices and factors derived from fibre dimensions are equally important as fibre morphology while considering raw material for pulp and paper industry. Snook (1997) reported desirable values of runkel ratio, slenderness ratio and flexibility coefficients both in hardwoods and softwoods. According to him the values of runkel ratio, slenderness ratio and flexibility coefficients are 0 .35, 95-120 and 75 respectively for softwoods and 0.4-0.7, 55-70 and 55-75 respectively for hardwoods. In casuarina clones, slenderness ratio (118.752) and flexibility coefficient (76.38) are very close to the maximum values of these factors as in softwoods.

Runkel ratio which refers to the ratio between double the wall thicknesses and lumen diameter is a commonly used indicator of the collapsibility of tracheids (Evans *et al.*, 1997). Singh *et al.* (1991) reported that fibre characteristics such as the Runkel ratio and shape factor had marked influence on strength properties. The tensile index, tear index and burst index decreased with increase in the Runkel ratio and shape factor. Runkel ratio of fibres determines its felting power and flexibility. Pulps having very good flexibility and Runkel ratios can yield pulps with acceptable breaking length, tear and burst indices suitable for newsprint paper production (Jimenez *et al.*, 1993; Scott *et al.*, 1995). A number of researchers suggested an approximate range of runkel ratio applicable to pulp and paper production, 0.25 to 1.5 by Singh *et al.* (1991); less than 1 by Dadswell and Wardrop (1959) and less than or equal to 1 by Okereke (1962) and Rydholm (1965). In this study all the casuarina clones showed Runkel ratio higher than 1.5 which impacts negatively on tensile strength, tear strength and burst strength of paper.

Fibers with lower values of shape factor will give better strength to paper and lower tensile stiffness (Page and Seth, 1980). So species with lower shape factor is suitable as a raw material for pulping and paper making. Shape factor and solid factor were found to be related to the paper sheet density and could significantly be correlated to breaking length of paper in Eucalyptus (Ona *et al.*, 2001). According to Page and Seth (1980), lower the value of shape factor, higher will be the paper strength. As casuarina clones in this study showed moderate value of shape factor (0.7), it will result in moderate strength of pulp and paper.

Slenderness ratio is directly proportional to fibre length and inversely proportional to fibre cell wall thickness. Fibers having longer and thinner cell walls are producing a good slenderness ratio. Higher the slenderness ratio, greater will be the expected flexibility that will give better tensile and tear property. Slenderness ratio is also related with resistance to tearing (Rydholm, 1965). Dutt *et al.* (2004) reported that increase in slenderness ratio results in paper with low degree of collapsibility and conformability within the sheet. Lower the collapsibility value, more easy it is to drain water from the wet end of the paper-machine (Foelkel, 1998).

According to Ogbonnaya *et al.* (1997) fibres with poor slenderness ratio do not produce good surface contact and fiber-to-fiber bonding which reduces its mechanical strength properties. Fibres having high slenderness ratio is suitable for writing, printing, wrapping and packaging purposes. It is stated that if the slenderness ratio of a fibrous material is lower than 70, it is not valuable for quality pulp and paper production (Young, 1981; Bektas *et al.*, 1999). While considering slenderness ratio range recommended by Young (1981) and Bektas *et al* (1999), casuarina clones studied in this work are suitable for pulp and paper making as because of its higher slenderness ratio (> 70).

Flexibility coefficient is also referred to as Istas coefficient or elasticity coefficient or coefficient of suppleness and it is related with individual elasticity of fibers. Ogbonnaya *et al.* (1997) reported that the low flexibility produce a negative effect on tensile and bursting strengths as well as folding endurance of paper. According to Bektas *et al.*, (1999) there are four groups of fibers based on its elasticity rate

- 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

Peteri (1952), Okereke (1962) and Rydholm (1965) demonstrated that a higher flexibility coefficient (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). 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). Analysis of previous studies on importance of flexibility coefficient on pulp and paper making revealed that the casuarina clones are suitable for pulp and paper making while considering flexibility coefficient.

5.2.3 Chemical constituents

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. Cellulose and lignin are major structural as well chemical components of wood. Along with wood fibre morphology, wood chemistry also determines key paper qualities such as strength, opacity, porosity, and bulk (Cotterill and Macrae, 1997). Paper strength also depends on the lignin and cellulose content of raw plant materials. While considering pulp and paper making, the amount of cellulose in wood is positively related with pulping yield whereas lignin is negatively correlated (Amidon, 1981; Wallis *et al.*, 1996). Analysis of samples at various heights/lengths of the plant materials showed that lignin and cellulose content depends on tissue maturity, but does not change significantly within each species.

5.2.3a Cellulose content

According to the rating system developed by Nieschlag *et al.* (1960), plant materials with 34 and over cellulose content were characterized as promising for pulp and paper manufacture from a chemical composition point of view. According to Madakadze *et al.*, (1999) cellulose content is directly proportional to pulp mechanical strength and especially tensile strength. 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. In this study all the clones showed satisfactory levels of cellulose content (>40 %) for pulp and paper making.

5.2.3b Lignin content

Lignin is the most complex structural component of wood that corresponds to about 20-30% of the wood cell wall. Wood chemical composition varies with geographical origin, genus, species and positions within a tree. Usually lignin is an undesirable polymer and its removal during pulping requires high amounts of energy and chemicals. A significant variation in composition was found in the heterogeneity of lignin which has a large impact in the pulping industry. In general softwoods have higher lignin content (25-30%) while hardwoods have less lignin (18-30%). In the present study, all the clones showed acceptable range (<30 %) of lignin.

It has long been realized that lignin distribution influences almost all processes in which wood is converted to paper (Westermark *et al.*, 1988). The presence of lignin is generally regarded as undesirable in pulp and paper industries, primarily because it is responsible for the yellowing of paper based products over time if not effectively removed. The industry expends numerous energy and resources for removing lignin with a variety of chemical pulping and bleaching processes (Fromm *et al.*, 2003).

The present study revealed that Klason lignin contents were also at satisfactory levels (<30%) for all clones. Kojimal (2007) reported that klason lignin content in wood was inversely correlated with pulp sheet density, which is an important characteristic affecting the physical properties of pulp. 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). The range for lignin (%) for different eucalyptus species in these reports the value range was from 22.99-28.1 (Singh *et al.*, 1991). Low lignin content of casuarina clones makes it suitable for pulp and paper making.

5.4. Correlation analysis

Oven dry specific gravity and air dry specific gravity were positively related. Scientifically, these two density parameters are only differ because of the change in moisture content. Fibre length was positively related to fibre cell wall thickness and was negatively related to fresh weight specific gravity and fibre lumen width. Increase in growth rate results in an increase in overall dimensions of fibre. So any increase in fibre length contributes proportionate increase in fibre cell wall thickness. Increase in lumen width allows wood to hold more water which results in increase in fresh weight of the wood. High lumen width also represents high growth rate which is responsible for low fibre length. Fibre cell wall thickness was positively related to air dry specific gravity and negatively related to fibre lumen width. Increase in fibre cell wall thickness increases total biomass of wood that causes increase in the air dry specific gravity of wood. Usually, fibre with high lumen width will have low cell wall thickness. Fibre lumen width and fibre diameter are positively related to each other. Similar pattern of correlation between these variables was observd in a study by Taylor (1973) on *E.grandis* He observed a strong correlation between wall thickness and basic density (r=0.77). Fibre length was positively correlated with fibre diameter and wall thickness. Malan (1991) reported positive correlations between thickness and volumes of fibre walls and basic density and a weaker correlation between lumen diameter and fibre length. Sreevani and Rao (2013) between studied variation in basic density, fibre and vessel morphology of *Eucalyptus tereticornis* sm. Clones and found positive correlation between lumen diameter (r= 0.615) and wall thickness and between fibre diameter (r=0.627) and wall thickness.

5.5 Screening of different plus trees on the basis of wood properties and growth

In this study, hierarchical cluster analysis of *Casuarina equisetifolia* L. clones considering growth, anatomical, physical and chemical parameters was carried out. Forty six clones were grouped in to 4 clusters (Figure 2). Cluster 1 was found highly divergent from the other two clusters. Cluster 4 having only one clone (clone 47), showed higher values for majority of growth, anatomical, physical and chemical properties. In the case of pulp and paper making properties (ratios and factors) also, cluster 4 showed acceptable ranges of values compared to others. While considering growth, physical, anatomical and chemical properties, Cluster 4 was followed by cluster 2, cluster 1 and cluster 3 in terms of its suitability for pulp and paper making.

5.5 Conclusion

Wood properties are changing throughout the world (Zobel *et al.*, 1983). Its variability and diversity makes it useful for many kinds of products. In order to use wood efficiently, the variation pattern within trees, among trees within species, and among species must be understood. This also requires some knowledge of the causes of variation and the effects. Deep knowledge about the variations in wood properties, their control, and their effect on the quality on the end products is very necessary for the improvement of the quality of final products. In the present study variations among clones of casuarina was studied for sorting out superior clones suitable for the purpose of pulp and paper making.

There is considerable evidence in the literature which showed significant inter- and intra-clonal variation in wood properties between clones. Similarly the present study also showed significant inter- and intra-clonal variation in almost all the wood properties studied. Variation in wood properties of clones helped to sort out superior clones for pulp and paper making. Wood properties such as specific gravity, fibre morphology, ray and vessel morphology and chemical constituents influences pulp and paper properties. The results of the present study showing these properties and their acceptable range are shown in Table 15.

Table 15: Wood physical, anatomical and chemical properties and fibre derived ratios of *Casuarina equisetifolia* L. and their acceptable range for pulp and paper making

Wood properties	*Casuarina equisetifolia* L.	Acceptable range
Specific gravity (oven dry)	0.741	≤ 0.600 (Chittenden and palmer, 1990)
Fibre length (μm)	1459.65	longer the better (Wimmer *et al*., 2002)
Runkel ratio	1.897	≤ 1 (Okereke, 1962)
Shape factor	.7391	lower the better (Page and Seth, 1980)
Slenderness ratio	118.752	> 70 (Young, 1981; Bektas *et al*., 1999)
Coefficient of flexibility	76.38	> 60 (Peteri, 1952; Okereke, 1962; Rydholm, 1965)
Coefficient of rigidity	62.0106	lower the better (Hus *et al*., 1975)
Cellulose content (%)	46.40	> 34% (Nieschlag *et al*., 1960)

IFGTB had ranked all 46 clones based on growth traits. The top fifteen clones thus ranked by IFGTB based on growth performance were Clone 1, Clone 5, Clone 11, Clone 30, Clone 41, Clone 44, Clone 45, Clone 46, Clone 47, Clone 49, Clone 51, Clone 56, Clone 60, Clone 63 and Clone 68. In the present study, clones were grouped into clusters and then clusters were ranked based on fibre derived ratios and factors, physical and anatomical properties influencing pulp and paper quality. Clones belonging to cluster 4 has ranked first in majority of these parameters viz., air dry specific gravity, fibre length, fibre diameter, fibre lumen width, runkel ratio, rigidity coefficient, flexibility coefficient, shape factor, vessel diameter and vessel area. Cellulose and lignin content of cluster 4 were also found to be within the acceptable range for pulp and paper making. Clones belonging to cluster

2 ranked second with respect to overall performance in physical and anatomical properties and fibre derived ratios and factors. (table 15). Cluster 4 included only one clone; clone 47, while cluster 2 included clone 1, clone 41, clone 44, clone 45, clone 46, clone 51, clone 56, clone 60, clone 68, clone 88 and clone 90. Out of these 12 clones, ten clones viz. clone 1, clone 41, clone 44, clone 45, clone 46, clone 47, clone 51, clone 56, clone 60 and clone 68 were listed as superior clones by IFGTB based on the growth performance.

Table 16: Ranking of clones based on fibre derived ratios and factors, physical and anatomical properties.

Properties	Rank I	Rank II
Oven dry specific gravity	Cluster 2	Cluster 4
Fibre length	Cluster 4	Cluster 1
Fibre width	Cluster 4	Cluster 2
Fibre lumen width	Cluster 4	Cluster 1
Fibre wall thickness	Cluster 2	Cluster 4
Runkel ratio	Cluster 4	Cluster 2
Slenderness ratio	Cluster 1	Cluster 3
Rigidity coefficient	Cluster 4	Cluster 1
Flexibility coefficient	Cluster 4	Cluster 1
Shape factor	Cluster 4	Cluster 2
Vessel length	Cluster 1	Cluster 3
Vessel area	Cluster 4	Cluster 2
Vessel diameter	Cluster 4	Cluster 2
Vessel frequency	Cluster 1 & 3	Cluster 2

SUMMARY

SUMMARY

A study titled "Wood property variation in selected clones of *Casuarina equisetifolia* L. grown in Karur district, Tamil Nadu for pulp and paper making." was carried out at the College of Forestry, Kerala Agricultural University, Vellanikkara, Kerala during 2011-2012. The salient findings of the study are as follows:

- Significant difference in specific gravity in three conditions viz., fresh, air dry and oven dry weight basis was observed among clones. Intra-clonal axial variation in specific gravity was significant only in air dry and fresh weight conditions. Specific gravity between axial positions specific gravity decrease from base to middle and then increases upwards, while maximum specific gravity observed at base positions.
- The maximum air dry, fresh weight and oven dry specific gravity was found in clone 56, clone 11 and clone 69 respectively and minimum in clone 85 and clone 1 and clone 85 respectively.
- Fibre length showed significant difference among clones and also between axial positions. Fibre length showed increasing trend from base to top after a small initial decease from base to middle. The maximum average fibre length was found in clone 4 and the minimum for clone 45.
- Fibre diameter was found to have significant difference between clones and axial positions within the clones. In this study, clone 61 had the highest value and clone 90 had lowest value for fibre diameter.
- Significant difference in fibre wall thickness was found between clones and axial positions within the species. Among 46 clones, clone 56 had the highest fibre wall thickness and the lowest for clone 29.
- The variation in fibre lumen diameter was found to be significant between axial positions but not between clones.

- All the fibre parameters increased with increase in height after a small initial decrease from base to middle. Cell wall thickness however did not show any decrease between base and middle positions.
- Pooled average of all these parameters revealed the fact that clones are suitable for pulp and paper making when fibre length was considered.
- Among Runkel ratio, slenderness ratio, rigidity coefficient, flexibility coefficient and shape factor, inter-clonal variation was found to be significant only with respect to slenderness ratio. Within clonal variation was significant with respect to all these parameters.
- Pooled averages of all clones for these parameters showed that slenderness ratio, flexibility coefficient and shape factor are within the acceptable range for pulping and paper making.
- Ray height, ray width and ray frequency variation was found to be significant among clones. Ray height was found to be maximum for clone 1 and minimum for clone 1. Clone 1 and clone 2 have the maximum and minimum values of ray width. Ray frequency was highest for clone 2.
- Vessel length variation was significant between and within clones. Vessel area, vessel diameter and vessel frequency showed significant difference between clones.
- Cellulose and lignin content were found to differ between clones. Cellulose content was found to be highest in clone 1 and lowest in clone 2. On the other hand, lignin content was highest for clone 1 and lowest for clone 2. Percentage cellulose and lignin content of all clones was within the acceptable range for pulp and paper making.
- Among the four clusters, the highest values of specific gravity (air dry) and specific gravity (fresh weight) were for cluster 4 and specific gravity (oven dry) for cluster 2. The lowest values of specific gravity (air dry), specific gravity (fresh weight) and specific gravity (oven dry) were for cluster 3, cluster 4 and cluster 3 respectively.

- Cluster 4 showed the highest values for fibre length, fibre diameter and fibre lumen width whereas the highest value of fibre wall thickness was for cluster 2.
- Runkel ratio, slenderness ratio, rigidity coefficient, flexibility coefficient and shape factor was highest for cluster 3, cluster 1, cluster 2, cluster 4 and cluster 3 respectively. Cluster 4 showed the lowest values of all the ratios and factors except flexibility coefficient whereas it was lowest for cluster 3.
- Both vessel area and vessel diameter was highest for cluster 2. Cluster 4 showed highest values of both vessel frequency and vessel length. The lowest values of vessel area and vessel diameter were measured in cluster 4. Both cluster 1 and cluster 3 had the lowest value of vessel frequency. Vessel length was lowest for cluster 3.
- Both ray width and ray frequency was highest for cluster 4 and ray height for cluster 2. The lowest ray height, ray width and ray frequency was measured in cluster 4, cluster 3 and cluster 2 respectively.
- Cluster 4 and cluster 2 were ranked first and second respectively based on overall performance of physical, anatomical and chemical properties and also based on fibre derived ratios and factors influencing pulp and paper qualities.

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APPENDICES

APPENDIX

I. Mean specific gravity (air dry) of clones at different axial positions

	Specific gravity (Air dry)								
Clone no.	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	0.783	0.711	0.737	0.744	55	0.819	0.865	0.847	0.844
3	0.792	0.798	0.784	0.791	56	0.887	0.839	0.881	0.869
4	0.801	0.787	0.807	0.798	58	0.809	0.815	0.818	0.814
5	0.846	0.811	0.838	0.832	59	0.768	0.787	0.815	0.790
11	0.715	0.842	0.815	0.791	60	0.795	0.775	0.791	0.787
12	0.685	0.742	0.751	0.726	61	0.769	0.702	0.745	0.739
20	0.758	0.690	0.760	0.736	62	0.722	0.689	0.684	0.698
25	0.845	0.845	0.780	0.823	63	0.778	0.766	0.797	0.780
29	0.852	0.830	0.801	0.828	64	0.856	0.864	0.837	0.852
30	0.759	0.734	0.759	0.751	66	0.858	0.860	0.866	0.861
31	0.869	0.816	0.850	0.845	68	0.763	0.751	0.739	0.751
33	0.855	0.871	0.867	0.864	69	0.871	0.865	0.868	0.868
35	0.805	0.753	0.756	0.771	72	0.859	0.836	0.825	0.840
41	0.720	0.846	0.802	0.789	73	0.844	0.865	0.845	0.851
44	0.788	0.754	0.809	0.784	74	0.767	0.736	0.781	0.761
45	0.815	0.822	0.775	0.804	83	0.815	0.800	0.793	0.803
46	0.769	0.796	0.807	0.791	84	0.866	0.841	0.818	0.842
47	0.884	0.831	0.813	0.843	85	0.670	0.600	0.635	0.635
48	0.788	0.868	0.883	0.847	86	0.827	0.792	0.779	0.800
49	0.781	0.771	0.775	0.776	87	0.742	0.773	0.761	0.759
51	0.893	0.825	0.830	0.849	88	0.833	0.778	0.782	0.798
53	0.730	0.747	0.709	0.729	89	0.734	0.736	0.762	0.744
54	0.796	0.779	0.764	0.780	90	0.791	0.724	0.750	0.755

II. Mean specific gravity (fresh weight) of clones at different axial positions

	Specific gravity (fresh weight)								
Clone no.	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	1.086	1.041	1.013	1.047	55	1.171	1.129	1.183	1.161
3	1.211	1.159	1.206	1.192	56	1.174	1.152	1.174	1.167
4	1.165	1.133	1.139	1.145	58	1.167	1.162	1.169	1.166
5	1.172	1.143	1.169	1.161	59	1.150	1.142	1.172	1.155
11	1.458	1.221	1.209	1.296	60	1.094	1.060	1.110	1.088
12	1.178	1.189	1.192	1.186	61	1.201	1.177	1.182	1.187
20	1.094	1.086	1.109	1.097	62	1.166	1.299	1.167	1.211
25	1.216	1.225	1.178	1.206	63	1.096	1.082	1.075	1.084
29	1.182	1.165	1.176	1.174	64	1.190	1.217	1.202	1.203
30	1.101	1.096	1.102	1.100	66	1.335	1.162	1.223	1.240
31	1.235	1.178	1.224	1.212	68	1.167	1.128	1.175	1.157
33	1.088	1.103	1.110	1.100	69	1.198	1.204	1.224	1.209
35	1.220	1.205	1.194	1.207	72	1.182	1.177	1.201	1.187
41	1.193	1.223	1.210	1.208	73	1.164	1.152	1.146	1.154
44	1.155	1.094	1.150	1.133	74	1.140	1.159	1.143	1.147
45	1.208	1.147	1.192	1.182	83	1.196	1.171	1.205	1.191
46	1.159	1.163	1.183	1.168	84	1.235	1.219	1.214	1.223
47	1.141	1.117	1.130	1.129	85	1.177	1.147	1.216	1.180
48	1.208	1.212	1.235	1.218	86	1.216	1.204	1.201	1.207
49	1.116	1.104	1.201	1.140	87	1.092	1.122	1.139	1.118
51	1.152	1.096	1.112	1.120	88	1.184	1.189	1.159	1.177
53	1.184	1.197	1.147	1.176	89	1.051	1.034	1.068	1.051
54	1.058	1.078	1.067	1.068	90	1.112	1.056	1.062	1.077

III. Mean specific gravity (oven dry) of clones at different axial positions

	Specific gravity (oven dry)								
Clone no.	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	0.719	0.679	0.675	0.691	**55**	0.773	0.756	0.761	0.763
3	0.734	0.722	0.780	0.745	**56**	0.826	0.775	0.832	0.811
4	0.741	0.768	0.717	0.742	**58**	0.750	0.790	0.789	0.776
5	0.788	0.764	0.775	0.775	**59**	0.710	0.745	0.771	0.742
11	0.737	0.707	0.738	0.728	**60**	0.786	0.783	0.790	0.786
12	0.705	0.674	0.686	0.688	**61**	0.723	0.671	0.733	0.709
20	0.732	0.666	0.697	0.698	**62**	0.692	0.644	0.670	0.669
25	0.721	0.791	0.750	0.754	**63**	0.699	0.705	0.736	0.713
29	0.776	0.753	0.720	0.750	**64**	0.821	0.809	0.811	0.814
30	0.740	0.722	0.717	0.726	**66**	0.776	0.823	0.818	0.806
31	0.817	0.797	0.825	0.813	**68**	0.718	0.754	0.675	0.715
33	0.762	0.755	0.758	0.758	**69**	0.845	0.810	0.835	0.830
35	0.770	0.723	0.722	0.738	**72**	0.767	0.752	0.779	0.766
41	0.673	0.770	0.726	0.723	**73**	0.783	0.820	0.792	0.798
44	0.746	0.708	0.753	0.736	**74**	0.726	0.748	0.724	0.733
45	0.795	0.778	0.754	0.776	**83**	0.782	0.763	0.712	0.752
46	0.730	0.736	0.768	0.745	**84**	0.765	0.724	0.789	0.759
47	0.732	0.776	0.720	0.743	**85**	0.633	0.535	0.613	0.594
48	0.728	0.767	0.742	0.746	**86**	0.753	0.702	0.720	0.725
49	0.739	0.729	0.727	0.732	**87**	0.732	0.740	0.719	0.730
51	0.763	0.757	0.776	0.765	**88**	0.751	0.725	0.738	0.738
53	0.714	0.706	0.665	0.695	**89**	0.679	0.686	0.677	0.680
54	0.746	0.730	0.715	0.730	**90**	0.724	0.670	0.682	0.692

IV. Results of ANOVA table for comparing specific gravity (air dry)

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	1.6922	0.0376	9.812**	0.00
Within clones	92	0.3526	0.0038	1.952**	0.00
Error	552	1.0837	0.002		
Total	689	3.1286			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

V. Results of ANOVA table for comparing specific gravity (fresh weight)

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	1.8707	0.0416	7.249**	0.00
Within clones	92	0.5276	0.0057	1.839**	0.00
Error	552	1.7209	0.0031		
Total	689	4.1192			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

VI. Results of ANOVA table for comparing specific gravity (oven dry)

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	1.2804	0.0285	9.336**	0.00
Within clones	92	0.2804	0.003	1.118^{ns}	0.23
Error	552	1.5049	0.0027		
Total	689	3.0657			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

VII. Mean fibre length of clones at different axial positions

	Fibre length (µm)								
Clone no.	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	1447.60	1415.50	1560.25	1474.45	**55**	1564.90	1489.00	1594.30	1549.40
3	1358.00	1355.00	1333.50	1348.83	**56**	1627.85	1518.50	1650.05	1598.80
4	1698.74	1773.63	1707.11	1726.49	**58**	1445.20	1331.70	1249.70	1342.20
5	1438.20	1528.50	1406.25	1457.65	**59**	1408.50	1469.00	1342.75	1406.75
11	1315.25	1460.80	1341.60	1372.55	**60**	1403.20	1435.65	1488.60	1442.48
12	1306.80	1439.25	1415.60	1387.22	**61**	1710.75	1587.25	1583.50	1627.17
20	1400.75	1346.15	1393.00	1379.97	**62**	1209.25	1383.00	1322.35	1304.87
25	1616.75	1606.55	1358.50	1527.27	**63**	1469.80	1559.80	1502.00	1510.53
29	1178.00	1407.12	1590.34	1391.82	**64**	1489.00	1413.75	1496.70	1466.48
30	1564.80	1442.00	1494.90	1500.57	**66**	1719.20	1376.25	1791.90	1629.12
31	1443.25	1253.35	1435.75	1377.45	**68**	1308.60	1353.00	1541.45	1401.02
33	1463.50	1436.75	1490.95	1463.73	**69**	1371.75	1749.50	1415.50	1512.25
35	1486.75	1488.25	1380.00	1451.67	**72**	1441.90	1652.25	1623.25	1572.47
41	1449.95	1358.75	1272.75	1360.48	**73**	1273.75	1381.80	1319.48	1325.01
44	1436.75	1422.85	1361.80	1407.13	**74**	1717.00	1617.50	1576.20	1636.90
45	1137.40	1189.00	1350.40	1225.60	**83**	1354.75	1468.00	1465.60	1429.45
46	1503.90	1330.25	1430.10	1421.42	**84**	1524.48	1549.00	1433.95	1502.48
47	1498.00	1562.50	1391.50	1484.00	**85**	1383.10	1389.75	1507.75	1426.87
48	1570.69	1565.10	1400.00	1511.93	**86**	1488.74	1495.90	1424.90	1469.85
49	1510.55	1536.55	1302.40	1449.83	**87**	1452.20	1348.00	1477.35	1425.85
51	1523.35	1371.20	1507.65	1467.40	**88**	1453.50	1518.50	1491.50	1487.83
53	1421.65	1428.50	1544.25	1464.80	**89**	1442.21	1446.60	1302.40	1397.07
54	1337.35	1310.62	1507.30	1385.09	**90**	1397.25	1200.50	1327.80	1308.52

VIII. Mean fibre diameter of clones at different axial positions

	Fibre diameter (µm)								
Clone no.	**Position**				**Clone no.**	**Position**			
	Base	**Middle**	**Top**	**Total**		**Base**	**Middle**	**Top**	**Total**
1	25.86	26.69	23.93	25.49	**55**	26.07	24.26	30.05	26.79
3	24.90	20.62	22.62	22.71	**56**	29.24	25.37	27.04	27.21
4	20.76	22.00	23.72	22.16	**58**	20.55	25.38	31.31	25.75
5	24.21	23.45	24.35	24.00	**59**	27.17	24.28	25.04	25.49
11	22.00	25.10	21.72	22.94	**60**	27.66	23.03	27.10	25.93
12	30.07	27.31	27.31	28.23	**61**	29.38	26.76	32.69	29.61
20	22.55	23.03	28.62	24.74	**62**	22.70	24.36	23.72	23.59
25	29.52	29.10	23.93	27.52	**63**	26.55	28.48	28.21	27.75
29	18.76	23.38	22.83	21.66	**64**	24.62	28.21	26.69	26.51
30	24.21	27.17	21.52	24.30	**66**	30.54	28.07	28.55	29.05
31	24.14	24.05	25.24	24.48	**68**	23.10	24.07	23.51	23.56
33	24.35	25.66	22.67	24.23	**69**	23.47	23.24	25.54	24.08
35	25.63	22.34	27.10	25.02	**72**	21.85	22.83	19.31	21.33
41	26.07	26.69	29.99	27.58	**73**	23.10	21.59	24.14	22.94
44	29.31	26.14	26.00	27.15	**74**	25.03	26.00	25.17	25.40
45	28.00	26.33	24.14	26.16	**83**	24.83	26.62	27.51	26.32
46	24.69	25.51	23.01	24.40	**84**	25.31	25.06	24.90	25.09
47	26.35	24.69	28.83	26.62	**85**	22.62	24.62	28.55	25.27
48	28.77	23.31	25.79	25.96	**86**	23.59	25.57	24.48	24.55
49	25.31	25.70	24.35	25.12	**87**	27.52	24.97	24.90	25.79
51	28.62	24.55	24.69	25.95	**88**	23.31	23.39	26.69	24.46
53	24.29	26.41	26.07	25.59	**89**	24.44	23.59	22.81	23.61
54	26.41	25.72	26.24	26.13	**90**	20.90	21.52	19.66	20.69

IX. Mean fibre lumen width of clones at different axial positions

	Fibre lumen width (µm)								
Clone no.	**Position**				**Clone no.**	**Position**			
	Base	**Middle**	**Top**	**Total**		**Base**	**Middle**	**Top**	**Total**
1	10.69	11.03	7.94	9.89	**55**	6.55	8.97	14.73	10.08
3	9.52	7.93	7.45	8.30	**56**	11.23	6.57	7.10	8.30
4	8.62	5.24	12.21	8.69	**58**	7.11	9.10	16.00	10.74
5	6.83	6.86	7.66	7.11	**59**	12.14	8.28	10.76	10.39
11	7.90	9.86	10.07	9.28	**60**	13.25	10.45	10.14	11.28
12	15.59	10.07	10.24	11.97	**61**	11.38	10.76	12.69	11.61
20	9.27	8.00	11.03	9.44	**62**	7.07	7.86	8.70	7.88
25	9.39	11.66	7.58	9.54	**63**	10.41	12.35	14.21	12.32
29	7.53	6.83	12.14	8.83	**64**	7.98	11.48	10.07	9.84
30	10.76	14.14	5.89	10.26	**66**	32.18	9.97	11.79	17.98
31	5.93	9.20	11.10	8.75	**68**	8.14	9.29	8.96	8.79
33	11.66	9.82	6.74	9.40	**69**	6.73	5.78	7.20	6.57
35	9.86	7.83	12.48	10.06	**72**	6.29	10.80	5.31	7.47
41	9.31	9.92	14.83	11.35	**73**	9.59	6.48	7.27	7.78
44	12.62	9.38	9.38	10.46	**74**	11.66	13.45	11.17	12.09
45	15.85	13.54	8.19	12.53	**83**	7.17	12.43	10.17	9.92
46	6.69	7.99	6.90	7.19	**84**	11.64	7.28	8.48	9.13
47	10.97	8.48	14.62	11.36	**85**	6.35	8.55	10.77	8.55
48	10.46	7.59	12.54	10.19	**86**	8.21	9.01	9.38	8.86
49	11.10	7.70	10.28	9.69	**87**	13.72	10.62	8.90	11.08
51	8.48	7.31	14.18	9.99	**88**	8.74	9.58	12.90	10.41
53	8.73	11.55	10.35	10.21	**89**	8.35	7.24	7.50	7.69
54	10.97	8.90	8.17	9.35	**90**	7.03	6.54	7.58	7.05

X. Mean of fibre wall thickness of clones at different axial positions

	Fibre wall thickness(µm)								
Clone no.	**Position**				**Clone no.**	**Position**			
	Base	**Middle**	**Top**	**Total**		**Base**	**Middle**	**Top**	**Total**
1	7.17	7.90	7.86	7.64	**55**	9.76	7.50	7.37	8.21
3	7.72	6.33	7.75	7.27	**56**	9.09	9.33	9.59	9.34
4	4.69	7.68	4.83	5.73	**58**	6.89	8.02	7.81	7.57
5	8.83	8.48	8.27	8.53	**59**	7.62	7.74	7.28	7.55
11	7.19	7.50	6.23	6.97	**60**	7.12	7.01	8.58	7.57
12	7.12	8.73	8.63	8.16	**61**	8.86	8.12	10.01	9.00
20	6.58	7.48	8.88	7.65	**62**	7.51	8.06	7.51	7.69
25	9.95	8.00	7.96	8.64	**63**	7.90	8.31	6.89	7.70
29	4.48	7.72	5.77	5.99	**64**	8.22	8.23	8.32	8.26
30	6.64	6.54	7.94	7.04	**66**	8.48	9.15	8.21	8.61
31	9.07	7.49	7.01	7.86	**68**	7.52	7.30	7.13	7.32
33	6.08	7.95	7.96	7.33	**69**	8.35	8.69	9.00	8.68
35	7.83	7.37	7.24	7.48	**72**	7.17	5.59	6.42	6.40
41	8.48	8.37	7.38	8.07	**73**	6.48	6.83	8.08	7.13
44	8.46	8.44	8.58	8.49	**74**	6.66	6.51	6.94	6.70
45	6.04	6.22	8.03	6.77	**83**	8.82	6.90	8.68	8.13
46	8.97	8.48	7.79	8.42	**84**	6.67	8.51	8.39	7.86
47	7.95	8.19	7.18	7.77	**85**	7.99	8.12	8.93	8.35
48	9.30	7.61	6.70	7.87	**86**	7.73	8.45	7.64	7.94
49	7.56	8.80	7.02	7.79	**87**	6.83	7.00	7.90	7.24
51	9.97	8.66	6.17	8.27	**88**	7.04	6.72	12.90	8.88
53	7.82	7.48	8.07	7.79	**89**	8.06	8.21	7.82	8.03
54	7.77	8.52	8.98	8.42	**90**	7.30	7.51	6.25	7.02

XI. Results of ANOVA table for comparing fibre length

Source	df	SS	MS	F value	P value
Between clones	45	6.3726E+06	141613.4261	3.264**	0.00
Within clones	92	3.9918E+06	43389.445	1.507**	0.00
Error	552	1.5893E+06	28791.6505		
Total	689	2.6257E+06			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

X11. Results of ANOVA table for comparing fibre diameter

Source	df	SS	MS	F value	P value
Between clones	45	2534.64	56.33	2.818**	0.00
Within clones	92	1839.03	19.99	1.639**	0.00
Error	552	6730.58	12.19		
Total	689	11104.24			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XII1. Results of ANOVA table for comparing fibre lumen width

Source	df	SS	MS	F value	P value
Between clones	45	2512.83	55.84	1.29^{ns}	0.15
Within clones	92	3983.85	43.30	1.805**	0.00
Error	552	13246.13	24.00		
Total	689	19742.81			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

X1V. Results of ANOVA table for comparing fibre cell wall thickness

Source	df	SS	MS	F value	P value
Between clones	45	384.1711	8.5371	1.774**	0.01
Within clones	92	442.8340	4.8134	1.843**	0.00
Error	552	1442.0120	2.6123		
Total	689	2269.0171			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XV. Mean runkel ratio of clones at different axial positions

	Runkel ratio								
Clone no.	**Position**				**Clone no.**	**Position**			
	Base	**Middle**	**Top**	**Total**		**Base**	**Middle**	**Top**	**Total**
1	1.39	1.45	2.37	1.74	**55**	3.01	1.99	1.21	2.07
3	1.73	1.68	2.47	1.96	**56**	1.87	3.08	2.94	2.63
4	1.16	3.17	1.02	1.79	**58**	2.18	1.95	1.03	1.72
5	3.36	2.68	2.36	2.80	**59**	1.56	1.92	1.79	1.75
11	1.96	1.68	1.57	1.74	**60**	1.17	1.50	1.80	1.49
12	0.95	1.94	1.75	1.55	**61**	1.81	1.56	1.66	1.67
20	1.60	1.93	1.64	1.72	**62**	2.45	2.18	1.81	2.14
25	2.31	1.45	2.31	2.02	**63**	1.67	1.60	1.00	1.43
29	1.34	2.33	0.98	1.55	**64**	2.25	1.92	1.76	1.98
30	1.36	0.93	3.36	1.88	**66**	1.33	2.07	1.96	1.79
31	3.22	1.82	1.33	2.13	**68**	2.09	1.59	1.70	1.79
33	1.18	1.97	2.42	1.86	**69**	2.60	3.34	2.55	2.83
35	1.62	2.01	1.33	1.65	**72**	2.41	1.06	2.73	2.07
41	1.97	1.79	1.03	1.60	**73**	1.44	2.39	2.51	2.12
44	1.34	1.88	1.95	1.72	**74**	1.17	1.06	1.25	1.16
45	0.79	1.08	2.25	1.37	**83**	2.80	1.26	2.00	2.02
46	2.84	2.34	2.41	2.53	**84**	1.29	2.68	2.29	2.09
47	1.46	2.11	1.08	1.55	**85**	2.67	2.03	1.85	2.18
48	1.88	2.28	1.07	1.74	**86**	2.01	1.92	2.17	2.03
49	1.61	2.68	1.39	1.89	**87**	1.14	1.55	2.00	1.56
51	2.47	2.52	0.91	1.97	**88**	1.85	1.67	2.00	1.84
53	1.92	1.40	1.63	1.65	**89**	2.22	2.40	2.35	2.32
54	1.59	2.13	2.48	2.07	**90**	2.24	2.32	1.90	2.16

XVI. Mean slenderness ratio of clones at different axial positions

Clone no.	Slenderness ratio								
	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	112.20	106.48	131.54	116.74	55	120.87	127.05	108.45	118.79
3	112.44	131.71	123.14	122.43	56	111.52	119.96	122.24	117.91
4	169.66	169.95	143.90	161.17	58	142.11	107.17	80.58	109.95
5	119.56	133.18	117.36	123.37	59	108.30	122.10	112.96	114.45
11	120.14	118.40	125.15	121.23	60	101.93	126.19	114.30	114.14
12	87.61	106.74	104.40	99.58	61	119.71	122.06	97.58	113.12
20	126.66	118.14	98.46	114.42	62	111.14	114.99	112.22	112.78
25	110.14	112.66	113.78	112.19	63	111.20	111.55	107.07	109.94
29	125.62	123.79	155.02	134.81	64	121.71	104.95	114.59	113.75
30	130.29	106.98	140.86	126.04	66	113.94	98.82	125.50	112.75
31	120.34	105.23	114.46	113.34	68	114.08	113.03	131.91	119.67
33	122.32	112.47	132.70	122.50	69	118.58	151.39	113.56	127.84
35	117.34	137.08	101.81	118.74	72	134.02	145.69	177.97	152.56
41	112.16	102.44	87.31	100.64	73	112.48	129.00	109.90	117.12
44	117.01	108.99	105.06	110.35	74	140.65	126.49	130.65	132.59
45	81.63	97.27	114.26	97.72	83	112.57	111.82	107.59	110.66
46	125.79	106.04	124.10	118.65	84	123.35	123.90	117.54	121.60
47	113.49	127.81	96.48	112.60	85	123.52	113.59	106.42	114.51
48	113.99	134.66	109.98	119.54	86	128.11	119.28	117.31	121.56
49	120.73	122.19	107.31	116.74	87	106.11	109.61	123.15	112.96
51	107.64	111.79	123.22	114.21	88	125.35	133.57	111.64	123.52
53	117.76	111.23	118.43	115.81	89	121.63	123.40	119.92	121.65
54	101.18	106.11	116.35	107.88	90	135.17	112.52	135.48	127.72

XVII. Mean rigidity coefficient of clones at different axial positions

	Rigidity coefficient								
Clone no.	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	55.64	59.18	65.20	60.00	55	74.47	61.72	50.17	62.12
3	62.54	61.45	69.63	64.54	56	61.92	73.47	70.85	68.75
4	44.11	68.07	41.74	51.31	58	67.65	63.06	50.27	60.33
5	73.59	71.73	67.89	71.07	59	58.16	63.58	60.29	60.68
11	65.90	58.47	58.36	60.91	60	51.71	61.25	62.10	58.36
12	47.59	64.68	63.42	58.57	61	60.37	61.04	61.64	61.02
20	58.26	64.77	61.77	61.60	62	67.71	66.19	63.46	65.79
25	67.75	54.41	66.51	62.89	63	59.39	59.20	48.54	55.71
29	47.65	65.89	50.30	54.61	64	66.69	60.69	62.75	63.38
30	55.39	47.83	75.19	59.47	66	56.31	65.36	58.59	60.09
31	74.96	62.30	55.68	64.32	68	65.75	60.71	60.45	62.30
33	49.53	62.13	70.12	60.59	69	71.40	74.95	70.71	72.35
35	60.75	66.56	53.36	60.23	72	64.70	48.38	67.08	60.05
41	65.41	61.91	49.56	58.96	73	56.48	63.08	67.09	62.21
44	57.59	64.59	66.41	62.86	74	53.02	50.28	55.15	52.81
45	43.12	48.46	67.46	53.02	83	71.96	51.81	62.77	62.18
46	73.09	66.39	68.04	69.17	84	53.17	67.81	67.25	62.74
47	60.23	66.76	50.18	59.06	85	71.18	66.22	62.21	66.53
48	64.07	65.39	51.50	60.32	86	64.97	66.59	63.89	65.15
49	60.98	68.32	57.59	62.30	87	50.41	55.73	64.33	56.82
51	69.78	70.76	49.09	63.21	88	60.25	58.10	95.68	71.35
53	64.57	57.17	62.10	61.28	89	66.51	70.42	69.65	68.86
54	59.43	66.38	68.83	64.88	90	70.28	69.40	63.57	67.75

XVIII. Mean flexibility coefficient of clones at different axial positions

Clone no.	Flexibility coefficient								
	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	82.53	82.82	67.27	77.54	55	50.66	74.47	95.72	73.61
3	74.95	76.85	64.24	72.02	56	77.44	51.68	52.86	60.66
4	83.65	48.96	100.36	77.66	58	68.49	71.58	101.38	80.48
5	55.02	59.35	63.05	59.14	59	85.08	68.54	81.34	78.32
11	70.71	80.21	89.93	80.28	60	95.39	88.92	76.19	86.83
12	102.68	73.21	74.78	83.56	61	77.11	80.51	76.85	78.16
20	82.43	69.78	77.46	76.56	62	60.24	64.30	72.86	65.80
25	63.38	82.09	63.34	69.60	63	78.69	84.92	102.11	88.57
29	80.52	58.12	105.51	81.38	64	64.88	76.49	74.86	72.08
30	87.68	104.57	52.42	81.56	66	202.64	70.71	80.68	118.01
31	49.26	76.52	87.92	71.24	68	69.08	77.40	76.57	74.35
33	95.89	76.29	59.61	77.26	69	56.76	49.19	56.54	54.16
35	77.37	69.21	92.07	79.55	72	59.41	95.36	54.14	69.64
41	70.87	75.83	98.18	81.63	73	81.59	60.44	59.90	67.31
44	86.30	71.89	71.68	76.62	74	93.74	103.35	89.18	95.42
45	113.25	99.80	65.70	92.91	83	55.93	93.73	74.95	74.87
46	53.34	62.93	59.52	58.60	84	90.99	58.38	68.10	72.49
47	83.55	67.92	100.62	84.03	85	55.41	69.07	75.93	66.80
48	73.35	64.83	97.96	78.71	86	70.73	70.18	74.50	71.80
49	85.96	60.13	84.53	76.87	87	98.35	85.98	69.24	84.52
51	58.91	59.15	114.28	77.45	88	74.51	79.97	95.68	83.39
53	71.46	86.12	79.00	78.86	89	67.49	60.19	64.70	64.13
54	81.91	69.28	61.69	70.96	90	66.52	61.18	77.01	68.23

XIX. Mean shape factor of clones at different axial positions

Clone no.	Shape factor								
	Position				Clone no.	Position			
	Base	Middle	Top	Total		Base	Middle	Top	Total
1	0.71	0.71	0.78	0.73	55	0.88	0.75	0.62	0.75
3	0.75	0.74	0.80	0.77	56	0.73	0.87	0.86	0.82
4	0.70	0.88	0.59	0.72	58	0.78	0.77	0.59	0.71
5	0.85	0.83	0.81	0.83	59	0.69	0.79	0.70	0.73
11	0.77	0.72	0.65	0.71	60	0.63	0.66	0.74	0.68
12	0.58	0.76	0.75	0.70	61	0.73	0.72	0.74	0.73
20	0.70	0.78	0.74	0.74	62	0.83	0.81	0.76	0.80
25	0.81	0.71	0.81	0.78	63	0.73	0.69	0.59	0.67
29	0.71	0.84	0.56	0.71	64	0.80	0.73	0.75	0.76
30	0.67	0.57	0.86	0.70	66	0.40	0.77	0.71	0.62
31	0.88	0.74	0.67	0.76	68	0.78	0.74	0.74	0.75
33	0.62	0.73	0.83	0.73	69	0.85	0.88	0.85	0.86
35	0.74	0.78	0.64	0.72	72	0.83	0.63	0.86	0.77
41	0.77	0.74	0.61	0.71	73	0.71	0.82	0.83	0.79
44	0.69	0.77	0.77	0.74	74	0.64	0.58	0.67	0.63
45	0.51	0.60	0.80	0.64	83	0.85	0.63	0.74	0.74
46	0.86	0.81	0.83	0.84	84	0.65	0.83	0.78	0.76
47	0.70	0.79	0.59	0.69	85	0.85	0.78	0.74	0.79
48	0.76	0.80	0.61	0.72	86	0.77	0.78	0.74	0.76
49	0.68	0.82	0.70	0.73	87	0.61	0.68	0.78	0.69
51	0.84	0.84	0.51	0.73	88	0.75	0.72	0.62	0.70
53	0.77	0.68	0.73	0.73	89	0.79	0.83	0.80	0.81
54	0.71	0.78	0.82	0.77	90	0.80	0.83	0.73	0.79

XX. Results of ANOVA table for comparing runkel ratio

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	82.0862	1.8241	1.122^{ns}	0.3160
Within clones	92	149.5532	1.6256	2.477**	0.0000
Error	552	362.1926	0.6561		
Total	689	593.8319			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XXI. Results of ANOVA table for comparing slenderness ratio

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	84595.8229	1879.9072	2.616**	0.0010
Within clones	92	66195.6831	719.5183	1.362*	0.0200
Error	552	291525.0076	528.1250		
Total	689	442316.5136			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XXII. Results of ANOVA table for comparing rigidity coefficient

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	15012.1833	333.6041	1.083^{ns}	0.3670
Within clones	92	28341.9544	308.0647	2.751**	0.0000
Error	552	61811.4912	111.9773		
Total	689	105165.6289	10.5166		

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XX1I1. Results of ANOVA table for comparing flexibility coefficient

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	76337.4060	1696.3868	1.034^{ns}	0.4370
Within clones	92	151005.6691	1641.3660	1.777**	0.0000
Error	552	509937.0259	923.7990		
Total	689	737280.1010			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XX1V. Results of ANOVA table for comparing shape factor

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	1.8185	0.0404	1.031^{ns}	0.4420
Within clones	92	3.6072	0.0392	2.36**	0.0000
Error	552	9.1705	0.0166		
Total	689	14.5963			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XXV. Mean vessel and ray parameters of clones

Clone number	Characters					
	Ray height (µm)	Ray width (µm)	Ray frequency (no/mm^2)	Vessel area (µm^2)	Vessel diameter (µm)	Vessel frequency (no/mm^2)
1	591.50	27.75	11	23059.31	143.00	9
3	452.50	30.50	13	12037.00	114.25	9
4	459.45	39.00	11	24390.60	148.75	8
5	420.25	27.75	18	28085.04	154.30	6
11	517.50	31.75	14	23112.65	146.50	13
12	503.50	36.25	13	31828.67	167.75	5

20	435.00	28.75	17	30215.89	161.50	7
25	388.75	26.50	17	27774.13	160.50	9
29	398.30	31.60	11	27981.20	148.00	5
30	516.75	36.75	12	32203.16	169.80	11
31	464.25	34.75	18	34093.55	175.25	6
33	485.25	25.50	18	28217.41	159.00	8
35	431.75	43.00	12	26013.40	152.00	7
41	491.50	32.50	12	19803.06	130.50	7
44	495.00	37.75	10	25039.28	144.75	8
45	533.00	27.50	12	23470.40	135.25	6
46	564.50	39.75	11	27457.70	156.50	8
47	441.25	34.50	16	25718.07	143.25	6
48	547.50	44.50	14	21408.81	140.00	9
49	482.00	39.50	14	17525.71	116.00	9
51	423.00	32.00	16	29047.15	159.25	7
53	450.25	26.00	13	23006.20	136.00	9
54	395.00	27.25	17	21415.56	129.75	8
55	555.60	27.75	17	27535.40	175.40	5
56	380.25	29.50	12	28295.60	156.50	7
58	410.25	25.50	16	17216.00	119.30	9
59	486.00	29.25	17	33631.00	169.60	9
60	462.25	31.50	11	33622.60	167.25	6
61	452.25	31.50	17	33559.49	171.00	5
62	501.75	32.50	12	36470.20	176.00	7
63	478.75	33.00	12	21920.82	136.25	7
64	425.00	26.75	14	23463.58	138.25	9
66	441.75	30.00	12	31241.20	149.00	9
68	363.25	27.75	13	25990.41	147.00	6
69	513.75	33.25	13	26484.52	155.75	6
72	521.00	27.25	15	25872.66	146.50	9
73	481.00	29.50	16	32195.18	171.50	7

74	477.50	31.50	16	21999.67	135.00	10
83	413.50	33.75	15	25554.01	161.76	6
84	413.00	28.50	14	30024.99	157.00	7
85	447.50	31.75	15	33520.33	176.00	9
86	420.75	29.75	23	27210.77	160.00	6
87	518.00	30.75	17	35883.37	173.50	7
88	409.75	35.25	18	27164.34	153.50	7
89	424.75	31.50	18	21045.69	136.00	8
90	449.00	29.00	15	29035.99	155.50	6
Total	463.79	31.69	14	26779.17	151.73	8

XXVI. Results of ANOVA table for comparing vessel length

Source	**Degrees of freedom**	**Sum of squares**	**Mean square**	**F value**	**P value**
Between clones	45	1.55446E+06	34543.4942	2.162**	0.001
Within clones	92	1.46961E+06	15973.9834	1.437**	0.008
Error	552	6.13471E+06	11113.6041		
Total	689	9.15877E+06			

** Significant at 1 % level; * Significant at 5 % level; ns non significant

XXV1I. Results of ANOVA table for comparing ray height

Source	**Degrees of freedom**	**Sum of squares**	**Mean square**	**F value**	**P value**
Between clones	45	6.1352E+05	13633.7198	1.846*	0.0030
Error	184	1.3587E+06	7383.9629		
Total	229	1.9722E+06			

** Significant at 1 % level; * Significant at 5 % level; ns-non significant

XXVIII. Results of ANOVA table for comparing ray width

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	4621.8492	102.7078	4.031**	0.0000
Error	184	4688.0750	25.4787		
Total	229	9309.9242			

** Significant at 1 % level; * Significant at 5 % level; ns-non significant

XXIX. Results of ANOVA table for comparing ray frequency

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	1565.4029	34.7867	11.856**	0.0000
Error	184	539.8624	2.9340		
Total	229	2105.2653			

** Significant at 1 % level; * Significant at 5 % level; ns-non significant

XXX. Results of ANOVA table for comparing vessel area

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	6.0953E+09	1.3545E+08	2.646**	0.0000
Error	184	9.4204E+09	5.1198E+07		
Total	229	1.5516E+10			

** Significant at 1 % level; * Significant at 5 % level; ns-non significant

XXXI. Results of ANOVA table for comparing vessel diameter

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	5.9058E+04	1.3124E+03	2.926**	0.0000
Error	184	8.2540E+04	4.4859E+02		
Total	229	1.4160E+05			

** Significant at 1 % level; * Significant at 5 % level; ns-non significant

XXXII. Results of ANOVA table for comparing vessel frequency

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Between clones	45	610.9904	13.5776	7.538**	0.0000
Error	184	331.4110	1.8011		
Total	229	942.4014			

** Significant at 1 % level; * Significant at 5 % level; ns-non significant

XXXIII. Height and DBH of all clones

Clone number	Height(m)	DBH(cm)	Clone number	Height(m)	DBH(cm)
1	11.13	6.95	**55**	9.70	5.30
3	10.83	7.01	**56**	11.22	7.66
4	11.31	6.94	**58**	9.25	5.54
5	11.42	7.02	**59**	10.35	6.73
11	11.26	7.06	**60**	11.26	8.09
12	11.89	6.65	**61**	9.86	6.77
20	10.14	6.95	**62**	10.60	7.18
25	11.12	6.81	**63**	10.59	7.06
29	11.06	7.03	**64**	10.25	6.46
30	10.70	7.05	**66**	11.17	6.85

31	11.39	6.87	**68**	10.53	7.66
33	10.86	6.94	**69**	10.72	6.68
35	9.04	4.56	**72**	9.77	5.97
41	11.48	7.43	**73**	10.08	4.91
44	11.49	7.71	**74**	10.22	7.00
45	11.88	7.56	**83**	10.95	6.39
46	11.06	7.56	**84**	11.44	6.60
47	12.11	8.68	**85**	10.53	5.66
48	10.62	6.57	**86**	10.05	6.78
49	11.13	6.98	**87**	11.33	6.75
51	11.33	7.62	**88**	11.22	7.86
53	10.50	7.09	**89**	10.58	7.05
54	10.39	6.35	**90**	10.45	7.82

ABSTRACT

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Variation in wood physical (specific gravity), anatomical (vessel and ray morphology) and chemical (cellulose and lignin per cent) properties of 46 casuarina (*Casuarina equisetifolia* L.) clones grown in Karur district, Tamil Nadu was studied to assess their suitability for pulp and paper making. Transverse discs collected from billets were converted to smaller specimens for undertaking studies on wood physical, chemical and anatomical properties. Estimation of specific gravity was undertaken using a precision balance and fibre morphology was studied using an image analysis system. Cellulose and lignin were estimated using standard procedures. Nested analysis of variance was carried out to find out inter and intra-clonal variation of clones. All the physical and anatomical properties except fibre lumen width, runkel ratio, rigidity coefficient, flexibility coefficient and shape factor, showed significant difference between clones. Within clone variation was also significant for all the physical and anatomical parameters except specific gravity (oven dry). In order to assess the suitability of clones for pulp and paper making, specific gravity (oven dry), fibre length, Runkel ratio, shape factor, slenderness ratio, flexibility coefficient, rigidity coefficient, and cellulose and lignin content were considered. Among these, fibre length, slenderness ratio, flexibility coefficient, shape factor and cellulose and lignin content of clones were found to be within the acceptable range for pulp and paper making. For selecting the best clones suitable for pulp and paper making, clones were grouped to four clusters by carrying out hierarchical cluster analysis on the basis of all physical, anatomical, chemical and growth parameters. Cluster 4 (one clone) and cluster 2 (11 clones) were found to be better for pulp and paper making in comparison to other clusters.

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THESIS

Submitted in partial fulfillment of the

requirement for the degree

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