PROVENANCE EVALUATION OF *Acacia mangium* Willd. FOR GROWTH AND WOOD TRAITS

by

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THESIS

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DECLARATION

I, hereby declare that this thesis entitle **"PROVENANCE EVALUATION OF *Acacia mangium* Willd. FOR GROWTH AND WOOD TRAITS"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled **"PROVENANCE EVALUATION OF *Acacia mangium* Willd. FOR GROWTH AND WOOD TRAITS"** is a record of research work done independently by Mr. Ringyao Jajo under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

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INTRODUCTION

1. INTRODUCTION

Forests and its products have been the source of livelihood for the evolution of mankind and with the progress of civilization with time, the diversification of its use and importance increased. It became the source of energy, revenue, raw materials for manufacturing units, etc. Wood is the prime product and it takes precedence of all the other products in terms of supplying raw material and revenue generation from a forest. Irrespective of the economy of a country, we continue to depend heavily upon forest for wood as raw materials. For instance, high-income countries like the United States of America, Austria, Italy, Finland, etc. features among the top five list in importing different wood products like industrial roundwood, sawnwood, wood-based panels, pulp for paper, etc., let alone the dependence of the low-income countries on the products (FAO. 2015). When it comes to India, the report showed that in 2013 the import of bleached sulphate pulp and chemical wood pulp alone touched 646030 and 724130 tons, respectively, which cost the exchequer of our country about US$ 503930. The imports of industrial roundwood cross 6.5 million m^3 at the costs of about US$ 2 million. Such demand, which is increasing with the burgeoning population of the world threaten the very existence of the forest, especially the primary forest which is declining at an alarming rate of 0.4 percent annually over a ten-year period in the world (GFRA, 2010) with increasing concerns of environmental issues. Therefore, promotion of plantations is the right step towards tackling these issues. A well planned plantation program with improved planting materials can augment the supply of forest products and reduce the pressure on the existing natural forest.

Species like *Acacia mangium* has great potential in such program because of its fast growing nature, multipurpose in use, wide adaptability to different environmental conditions and capacity to reclaim degraded land. It has been a priority species for industrial forest plantation program (Suhaendi, 1993) and has become popular and widely spread since its introduction to the world from its native site (Australia) in 1966 by D. I. Nicholson (National Research Council, 1983). It is the most widely planted *Acacia* species in the world (Gunn and Midgley, 1991; Turnbull *et al.*, 1998; Sein and Mitlohner, 2011). According to the Australian Tree Seed Centre (ATSC) which is the major agency involved in the collection, evaluation and export of Australian *Acacias,* the most sought-after *Acacia* species out of 322 species is *A. mangium* and with the highest request of seed from South East Asia (Griffin *et al.*, 2011).

Acacia mangium can grow up to a height of 25m to 35 m (Pinyopusarerk *et al.*, 1993) and capable of producing mean annual volume increment of 40 m^3 ha^{-1} yr^{-1} to 46 m^3 ha^{-1} yr^{-1} (Khasa *et al.*, 1995; Dhamodaran and Chacko, 1999). It reaches maximum MAI in volume at 6 to 9 years depending upon the site quality (Mead and Miller, 1991; Warren, 1991). It is primarily used for pulpwood (Griffin *et al.*, 2011). The basic density of pulpwood, which is desirable in terms of cost of production and yield of pulp, as well as the strength properties of paper produce from *A. mangium* is found to be on par with some of the commercialized and high-quality yielding species of *Eucalypts* (Logan, 1987). Besides, the unbarked wood of the species can also be used for kraft pulping (Logan and Balodis, 1982). It also has the potential for commercial production of veneer (Hamdan, 2011). In terms of revenue generation, its contribution is outstanding. Production of pulp alone from three *Acacia* species including *A. mangium* leads to the generation of US$900 million in Indonesia, Malaysia, Vietnam and China (Maslin and Orchard, 2013).

The utility of *A. mangium* as a timber species is on the increase world over primarily for furniture, plywood, poles, tool handles and agricultural implements. Practical knowledge suggests that its timber properties improve substantially at maturity (14-15 years). Moreover, wood of *A. mangium* has high calorific value (4800 kcal kg^{-1} to 4900 kcal kg^{-1}) suitable for use as fuelwood (Dhamodaran and

Chacko, 1999) and for production of good quality charcoal, wood pellets and activated carbon (Udarbe and Hepburn, 1987; Sein and Mitlohner, 2011). Moreover, the species can be multiplied easily through micropropagation (Crawford and Hartney, 1987).

Besides being widely adaptable to different environmental conditions, it can fix nitrogen in the soil. Therefore they can be used for reclamation of waste and degraded site where readily available minerals are deficient (Awang and Taylor, 1993; Thomas and Kent, 1987; Ferrari and Wall, 2004). They grow well in acidic soil (Turnbull *et al.*, 1998) as well as tolerate extended drought (Midgley and Vivekanandan, 1987) making it suitable for tropical areas where acidic soil is widespread and in region where long dry season prevails. This make the species ideal for adoption in plantation program in India where most of the plantation program is being established outside forest reserves, mostly in the wastelands (ICFRE, 2011).

In Kerala, *Acacia mangium* was first introduced in1980 and has spread in all the districts of the state. The warm and humid climate of the state provides an ideal condition for its growth. As a result the species has high growth potential. The species has the potential for used as commercial timber production (Shanavas and Kumar, 2006). This is significant in the present scenariao when there is increasing demand for used as solid wood purpose of the species, besides the rapid rise in demand of the species for pulp and paper production. Moreover, Kerala is a state where perennial based land use systems occupy 9.79% of the total geographical area of the state (FSI, 2013). Therefore, there is ample opportunity for production of wood materials of the species through promotion of plantation.

Despites its importance and demand, non availability of quality planting material is one of the primary concerns in the promotion of the species. Although many studies have been initiated for the species by various institute including the

Indian Council of Forestry Research and Education, most of the studies have been focusing on few parameters (Bhat *et al.*, 1985; Singh and Naithani, 1994; Indira, 1999; Anoop *et al.*, 2012; Shanavas and Kumar, 2006). Probably, the study conducted by Dhamodaran and Chacko (1999) was the most comprehensive work on *A. mangium* in Kerala, but the study also mostly confined to the growth attributes of the local seed source. Practically, no information is available on the superiority of *A. mangium* sources in terms of various properties *viz.* growth attributes, wood quality, utility as pulp and paper wood, etc., as well as no information on variability among provenances in terms of genetic parameters and genetic interrelations among growth traits of the species in the state. Hence, tree improvement initiatives are of paramount important for the species and provenance evaluation is the first logical step in this direction. The present study is an attempt to explore the variability in genetic traits among the existing provenances established for the purpose in Kerala.

The present study also investigated the variation in the morphometric traits of seeds, germination related parameters and the performances of progeny of the provenances. Variations in the morphometric trait reflect true genetic variation and the adaptability of species to different environmental conditions (Abdelbasit *et al.*, 2014). It also reflects the evolutionary response of a species in order to maximize their potential fitness and survive in the environment (Zhang, 1998). Documentation and analysis of the trait and their variation is an important parameter to identify the best provenance as well as from the view point of ecological functions. Similarly, germination related parameters and seedling performance, which decides the success of regeneration of a plantation, need to be taken into account to evaluate the variations that exist between provenances. Therefore, to cater the need for better understanding of the variation that exists in seedling to mature stages among the provenances of *A. mangium* used in the trial and facilitates selection, the present investigation had been carried out with the following objectives:

1. Evaluation of variation in growth attributes and wood properties of ten provenances and one local seed source of *Acacia mangium* grown in Livestock Research Station, Thiruvazamkunnu
2. Progeny evaluation.

The study comprised of three parts. Part I, comprised of the work and observations taken from the field performance of the 14 years old *A. mangium* trial plantation, Part II, Studies conducted for progeny evaluation including the morphometric traits and germination related parameters of seeds and in Part III, the variation in physical and mechanical properties of wood of the provenances were evaluated.

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

2.1 Taxonomy and distribution

Genus *Acacia* belong to the subfamily Mimosoideae of Leguminosae family. It consist of 1200 to 1300 species and it is widely distributed almost all over the world from Australia and the Pacific Island through Africa to the America (Turnbull *et al.*,1998). The Nomenclature Section of the XVII International Botanical Congress has reclassified the genus into subg. *Acacia*, subg. *Vachellia* and subg. *Senegali* in 2011 (Maslin and Orchard, 2013). *Acacia mangium* Willd. belongs to subgenus *Acacia*. It was first described and name as *Mangium* by Rumphius (National Research Council, 1983). It is used synonymously as *Racosperma mangium* and commonly known as Brown salwood.

Acacia mangium is naturally distributed in Indonesia to Irian Jaya, the Western Province of Papua New Guinea and northeast Queensland in Australia. The sites have mean annual rainfall of 1446 mm to 2970 mm and an altitudinal range of 3 m to 90 m. The upper limit of altitudinal range for the species is 780 m (Pinyopusarerk *et al.,* 1993). To the exception, *A. mangium* has been grown at an altitude of 1000 m and above and surprisingly the growth was remarkably good except for the development of poor stem form (Harwood and Williams, 1992; Weerawardane and Vivekanandan, 1991). It is a species of the humid, tropical lowland climatic zone characterized by a short winter and dry season not exceeding five months (Harwood *et al.,* 1998).

2.2 Provenance evaluation and its significance

The word "provenance" is a synonym for "origin" and "source" and it is defined as the original geographic source of a lot of seed or pollen (Wright, 1976). It is used interchangeably with geographic source or geographic race. Delineation of provenance is difficult unless a conspicuous and definite environmental separation exist. In absence of the condition, it becomes one of judgment and opinion to define a provenance (Zobel and Talbert, 1984). The differences between different countries of naturally occurring *A. auriculiformis*, which has more or less overlapping provenances with *A. mangium*, had been delineated or summarized by Pinyopusarerk *et al.* (1991). In the study, analysis of 28 provenances for 17 variates of the species revealed that the provenance can be clearly divided into three groups according to their geographical origins. They are Queensland, Northern Territory and Papua New Guinea.

Provenance test is an experiment in which seeds are collected from a number of widely scattered stands (usually natural), and the seedlings are grown under similar conditions. It can be done to test the suitability of exotic species to be introduced in the area or it can be a test to evaluate the variations and identify the best provenance suitable for the area for further breeding program where the species has already been introduced. Provenance tests date back to 18th century but the oldest well documented study is on Scots pine in 1821 by Frenchman, de Vilmorin (Wright, 1976). Since then, provenance research has gradually evolved from demonstration of importance of seed source to formulation of scientific principles and generalizing rules about geographic variations. Now the emphasis has shifted to practical experiment undertaken to discover the region capable of producing the best trees (Wright, 1981). Since early 19th century, it has been used for detecting populations with ecologically and economically desirable characteristics to be targeted for tree breeding program (Guries, 1990).

The first range-wide seed collections of *Acacia* species began in 1980. This followed an FAO recommendation that special attention be given to *A. mangium* with the view of establishing international provenance trials. Since then, there have been numerous collections of seeds of *Acacia* species in collaboration with Australian Tree

Seed Center by many institutes and organizations. By 1990, they had dispatched the seeds over 90 countries representing probably the most comprehensive early sampling ever for tropical tree species and reflect the acceptance of the potential of tree improvement of the species (Gunn and Midgley, 1991). Such range-wide collections of seeds and trials are important in order to detect the genetic differences that associates with the place of origin which is often several times greater than those among individual trees in the same stand (Wright, 1976).

Most plant species exhibit spatial structuring of genetic differences throughout their range (Hamrick and Godt, 1990) as a result of adaptation and evolutionary process of the species (Namkoong, 1981, O'Brien *et al.,* 2007). This provides evolutionary flexibility and determines the capacity of population to respond to future variations in the genetic and external environments (Namkoong, 1981; Lande and Shannon, 1996; Booth and Grime, 2003). Therefore, different provenances of same species grown together under same environmental condition can perform differently. Typical example recorded was from *Potentilla glandulosa*. When *P. glandulosa* derived from three different provenances – low elevation in the coast range of California, foothills of the Sierra Nevada Mountains and alpine regions of Sierra Nevada were grown in each of the environments showed different potential of growth. The coastal and foothill provenances did not thrive as well as they do in their native habitats. The coastal provenance became dormant during winter in the foothills and the foothill provenance remained active during the winter on the coast. When the coastal and foothill provenances were transplanted in the alpine zone, they seldom survived for a year and did not produce ripe seeds although they flowered. On the other hand, the alpine provenance exhibited dwarfism in its own environment and remained so when planted on the coast but they grew tall when planted in the foothills. Furthermore, when alpine provenance was planted on the coast they became very susceptible to diseases, injury due to dry summer and remained dormant in the winter (Dobzhansky, 1937).

Therefore, to assess such adaptive variations it is necessary to quantify the heritable and ecologically important traits by growing them at a common site so as to control in the best possible way, the phenotypic variation caused by the environment (Crandall *et al.,* 2000; McKay *et al.,* 2005). This also implies that optimal choice of provenance will be different from place to place (Raebild *et al.,* 2006). Therefore, selection of provenance should be done after careful evaluation of its performance prior to its introduction and such test should be done in the place where it is to be introduced. Another example that reinforced the need of such test is that when Indira **(**1999**)** conducted provenance trial of *A. mangium* from Papua New Guinea in India and Salazar (1989) in Costa Rica, it was found that Oriomo provenance was among the poor performer, while Silva *et al.* (1996) found that Oriomo provenance was the most promising provenance in Brazil. The consequences would be severe if it relied on the information conducted in Brazil and adopt them in India where environmental conditions are different. This clearly indicates the importance of evaluation of provenance at the place where it is to be introduced. Ignoring to follow such step and failure to integrate its use had lead to failures of over 30 percent of all improvement programs or had been only marginally successful (Khosla, 1981). That is why provenance evaluation is an absolute prerequisite for any tree improvement program (Lacaze, 1978). Lacaze (1978) also opined that it is quite feasible to double the production of plantation by means of utilization of good provenance derived from careful assessment of provenance variations.

2.3 Genetic diversity

Genetic variation is necessary to provide a basis for selecting the most suitable seed sources for planting and for developing appropriate strategies and base populations for tree breeding and conservation (Pinyopusarerk, 1993). Determining the amount, cause and nature of the variation in the species and how this variation can best be used is an important and initial step of improvement programs (Awang and

Bhumibhamon, 1993). Khosla (1981) aptly wrote "*Nature has created the variation; all we need to do is to be smart enough to recognize it, isolate it, package it in a desired tree and multiply it*". Therefore, before any studies are carried out, it is necessary to understand the variations that exist in *A. mangium* or any other species. This will strengthen the design to be used and which traits to be focused, keeping in mind the industrial requirement, for further improvement.

Two prominent studies, but contradictory findings have been reported for genetic diversity of *A. mangium.* Moran *et al.* (1989) observed that the genetic diversity of *A. mangium* using allozymes and found that the overall genetic diversity in the species was only 0.025, while the mean genetic diversity per population was just 0.017. Almost no genetic variation was observed in the Indonesian populations and the highest level of genetic diversity from Papua New Gunea. The genetic diversity of Cowley Beach populations in the study was found to be low. Therefore, they concluded that the species has low diversity, which may not be worth enough to investigate breeding system or estimate gene flow among populations. However, in contrary to the finding, Butcher *et al.* (1998) reported that the genetic diversity was high for the species. They studied the diversity in the nuclear genome of the species using 57 anonymous RFLP loci for 10 individuals from each of 10 natural populations representing the geographical range of the species. The result showed that the level of genetic diversity varied significantly among the populations and three to eight times higher than the diversity detected using allozymes. In the study, as against the finding of Moran *et al.* (1989), the overall genetic diversity of the species was found to be 0.195 and within population was 0.130. The alleles per locus varied from 1.0 to1.7 and percentage of polymorphic loci ranged from 1.8 to 57.9. Their study also reported the highest measures of genetic variations from Papua New Guinea population and lowest variation from Sidei and Ceram provenances. In addition to its diversity, superiority in performances of Papua New Guinea provenances has been advocated in many findings which will be discussed in the following sections.

Butcher *et al.*(1998) was of the view that the lower level of diversity in the allozyme surveys of Moran *et al.* (1989), might have arose owing to the differences in sampling strategies. Moreover, in terms of reliability, allozymes are gene products which exhibit the differences of only the protein coding genes whereas RFLPs reveal differences directly at the DNA level of both coding and non-coding regions, hence more reliable. Even so, the prediction of variation using molecular markers is still very poor (Karhu *et al.,* 1996**;** Nymbom and Bartish, 2000; McKay *et al.,* 2001; Reed and Frankham, 2001) because, quantitative traits are greatly influenced by the environmental parameters. Besides, epigenetic variability which is independent of genetic variability can be a potent source of variation (Vaughn *et al.,* 2007). As in case of *Pinus pinea*, regardless of its genetically depauperated nature, the species has high adaptive plasticity which could be differentiated between individuals or populations based on epigenetic variations rather than the genetic differences (Saez-Laguna *et al.*, 2014).

2.4 Amount and pattern of diversity

2.4.1 *Morphometric traits of seed*

Seedling performances of a species in a heterogenous environment has a functional relationship with the production of seed mass by the plant (Green and Juniper, 2004; Quero *et al.*, 2007). The seed size which has positive correlation with seed mass affect seedling height, diameter, leaf area, biomass and survival rate of seedlings (Bonfil, 1998). This is because higher seed mass indicates higher reserved food stored in seed which can be utilized for emergence and growth of seedling before it is able to photosynthesize. This relationship between seedling performances and seed mass varied depending upon the mother plant (Gonzalez-Rodriguez *et al.*, 2011). Moreover, the morphometric traits (length, width, thickness, weight or area) of seeds which influence the seed mass vary from species to species as well as within species of different provenances depending upon the genetic and environmental influence.

In *A. mangium,* the presence of high genetic variation of morphometric traits between various provenances have been reported by Salazar (1989). The estimated length of seed of different provenances in his study ranged from 3.2 to 4.3 mm and 2.3 to 2.8 mm for width, while the area ranged between 7.4 to 11.8 mm^2. The variations due to provenance for the species accounted for 93 percent of the total variation. Because of the presence of high variations in the morphometric traits, the number of seeds per kg varies greatly among provenances. Salazar (1989) reported that the average number of seeds varied from 95,607 to 145000 seeds kg^{-1}. While, Adjers and Srivastava (1993) found that the number of seeds per kg of *A. mangium* from individual trees collected from Australia, Indonesia and Papua New Guinea ranged from 76,922 to 125,000. However, both the studies revealed that Papua New Guinea provenance usually had larger seed size compared to other provenances. Study on 72 populations of *Aeschnomene americana* originating from 17 different countries also showed that there is high genetically based seed weight differentiation between provenances (Zhang, 1998). Similarly, high provenance variations in morphometric traits of seeds exist in other species.

Provenance variation in *Cordia* a*fricana* contributes about 71 percent to 98 percent to the total variation of seed morphometric traits (Loha *et al.,* 2006). Likewise, in *Senna siamea*, provenance variation contributes about 69 percent to 83 percent of the total variation except for the width of seed which is only 50 percent (Takuathung *et al.,* 2012). But the variation of seed length and weight between provenances are comparatively lesser than seed thickness and width of the species. In *Magnolia officinalis,* seed weight exhibited highest variation among fifteen Chinese provenances in seed morphometric traits (Shu *et al.,* 2012). This may not be the case for other species like *Acacia auriculiformis,* where no significant differences in morphometric traits exist between different provenances (Komar, 2001). The average weight of 1000 seeds of the species ranges from 12.74 to 15.62 g while average seed size ranges from 3.6 to 4.66 mm.

In addition to provenance effect there are reports of environmental influence over the morphometric traits. Loha *et al.* (2006) recorded strong environmental impact on the trait in *Cordia africana*. Zhang (1998) also reported that early flowering plant produces larger seeds than those that flowered later in the growing season of *Aeschynomene americana*. Besides the variables of plant, high positive correlation with altitude was found to be associated with the weight of seeds for the species. Similar finding of relationship between altitude and seed weight is reported by Uniyal *et al.* (2000) in *Grewia oppositifolia*. In *Magnolia officinalis,* seed weight was found to be negatively correlated with latitude of seed origin but positively correlated with temperature and rainfall (Shu *et al.,* 2012). This indicates that variables of plant and environmental condition especially at the time of seed development can shape the morphometric traits of a species (Rawat and Bakshi, 2011).

2.4.2 *Dormancy and germination of seed*

Dormancy is an innate property of the species and breaking the dormancy help in synchronizing the germination of seeds. Germination of seed requires stimulation of metabolic systems through imbibitions of water. This takes place when the seed coat facilitates the passage of water through the membrane else the seed remain dormant and the state is called physical dormancy (Baskin *et al.,* 2000). Many *Acacia* species exhibit physical dormancy (Kulkarni *et al.,* 2007) due to the presence of one or more palisade layers of lignified malphigian cells which make the seed coat water impermeable (Baskin, 2003).

Impermeability of seed coat to water is the major impeding factor for breaking physical dormancy. Manual scarification of this impermeable seed coat in *Astragalus arpilobus* showed that after 6 hours of placement in moistened filter paper, the increase in seed mass reaches more than 170 percent, while the non-scarified seed mass increases only about 5 percent even after 24 h (Long *et al.*, 2012). If the seed coat permeates water to pass through into the seed, it activates various metabolites which is controlled by the gene and in turn provides condition for germination of seeds. As a result, the scarified seeds of *A. arpilobus* began to germinate just after 6 days and reaches more than 95 percent after 28 days while, the germination percent of non-scarified seed was below 10 percent even after 28 days.

Germination of seed is a physiological process controlled by both the environment and genetic factors (Shu *et al.*, 2012). But the magnitudes of control over the process and response of species vary from species to species and within species as in case of *Acacia* species – *A. senegal* is more sensitive to water availability for germination than *A. seyal* (Kassa *et al.*, 2010). This is why variation of germination related characters exist in species and require different treatment to break the dormancy. In *Phragmites australis*, half of the viable seeds remain dormant at maturity and cold-stratification for 2 months at 4^0C prior to germination was applied, this result in higher germination percentage compared to warm-dry treated seed (Kettenring and Whigham, 2009). Likewise, the effectiveness of breaking seed dormancy for *Astragalus arpilobus* is high only through mechanical or acid scarification (Long *et al.*, 2012).

For *A. mangium*, pretreatment of seed with hot water at 100^0C is the most common method used to break dormancy (Adjers and Srivastava, 1993). Great care for temperature need to be taken while treatment of seeds for testing germination, because of its strong influence on germination process. Substantial amount of seeds (50%) of *A. mangium* failed to germinate when temperature fall below 90^0C (Bowen and Eusebio, 1981). They found the highest percentage of germination (91%) at 100^0C. Another treatment on the same species was conducted by exposing the seeds to dry heat in an oven at 100^0C for 5, 10, 15, 30 and 60 minutes. The experiment showed highest germination percentage (83%) for the seeds treated for 10 minutes.

Germination is never uniform as it varies with the genetic differences and the environmental variation (Bischoff *et al.*, 2006). Substantial variations in germination exist for *Acacia* species. *A. mangium* have high germination percentage compare to other *Acacia* species. The germination percentage of *A. mangium* was 82 percent when treated with hot water and sown in nursery bed while, *A. auriculiformis*, *A. aulacocarpa* and *A. crassicarpa* had 22 percent, 30 percent and 49 percent, respectively (Indira, 1999**)**. Another study conducted by Abari *et al.* (2012) showed that even when seeds of *A. oerfota* was treated in hot water and placed at germinator with regulated temperature and relative humidity, the percentage of germination was very low (< 50%). This indicates that performance in term of germination of *A. mangium* is much higher than other *Acacia* species. In addition to the differences in germination between the species, substantial variation in intra-species also exist (Karlsson and Milberg, 2008). But variation in seed germination of *A. mangium* of different provenances seems to be low. Indira (1999**)** tested seed germination of two provenances from Oriomo RWP of Papua New Guinea and seed orchard from Queensland and found that the germination percentage ranged from 78 percent to 86 percent. Similarly *A. auriculiformis* showed low variation between provenances (Komar, 2001).

On the other hand, variations among provenances within species for other species are conspicuous. In *Magnolia officinalis* the variation in seed germination between fifteen provenances ranged from 27 percent to 91 percent (Shu *et al.*, 2012). The average germination capacity of *Cordia africana* of six provenances ranged from 4 percent to 91 percent, likewise speed of germination of the species as determined by the germination energy exhibited high variation that ranged from 10 percent to 89 percent (Loha *et al.,* 2006). However, environmental effect on the speed of germination of the species was found to be high, while most of the total variations were attributed to provenance effect for germination capacity. Variation in seed germination between different provenances was reported to be high in *Grewia oppositifolia*. The variations among 30 provenances collected from India ranged from 25 percent to 91 percent (Uniyal *et al.,* 2000). Similarly, five provenances of *Legousia speculum-veneris, Echium vulgare, Cichorium intybus* and *Origanum vulgare* showed significant differences in the germination percentage (Bischoff *et al.*, 2006). It was observed that differences in germination were genetic (provenance) effect not the consequences of adaptive response to different environmental conditions.

The contribution of genetic influence to germination is further evident from the study conducted by Rawat and Bakshi (2011) in *Pinus wallichiana.* Germination of seed of the species collected from natural population with considerable geographic isolation from North-West Himalayan region of India showed high variation (19.8% to 68.7%). Coefficient of variation of germination for the species sown in nursery was 14.05 percent (laboratory – 36.3%). The genetic control over germination was found to be higher than the environmental effect. The genotypic coefficient of variance of the trait sown in nursery was 27.81 percent and environmental coefficient of variance was 13.24 percent, the difference was higher than the value estimated for the seeds tested in the laboratory. Heritability and genetic gain of the trait was high for the species because of the strong genetic influence. The estimated values of the traits sown in nursery was 81.55 percent (laboratory – 66.50%) and 51.74 percent (laboratory – 40.86%), respectively. Nevertheless, germination related characters can be modified by the environment (Scopel *et al.*, 2002) and rendered the contribution of provenance insignificant. Uniyal *et al.* (2000) recommended commencing of seed germination in nurseries only after the temperature rises above 20^0C for *Grewia* *oppositifolia* in India. As for the importance of provenance selection he has likened the right choice of selection of provenance as important as pretreatment.

2.4.3 *Seedling performance*

Seedling growth determines the success of plantation in the field. It is necessary to out-compete the obnoxious weed in order to regenerate an area. But just as any other traits of plant, seedling characters of a species are also influenced by both the genotype and environment. Greater the influence of genetics and higher the variations in the characteristic, it is more effective and better for selection through provenance test. However, maternal effects exert greatest influence on the growth of seedlings which diminishes with age, hence, not likely to be correlated with the performance of the individuals at a mature stage (O'Brien *et al.* 2007).

Salazar (1989) evaluated the performances of sixteen provenances of *A. mangium* in Costa Rica and found that significant differences existed between provenances. Large proportions of the observed variation in height (46%) and basal diameter (55%) at 3.5 months was found to be genetically controlled. He concluded that high genetic variation exist in the species for seedling characteristics. The total height of seedlings in the study varied between 17.7 cm to 34.6 cm and basal diameter ranged from 1.7 mm to 3.2 mm. In the study, Oriomo River provenance had the least performance. The provenances with the best growth at 3.5 months were from Indonesia, Papua New Guinea and Queensland.

On the contrary, the provenance trial of the species in India for nine provenances from Papua New Guinea revealed that *A. mangium* has moderate genetic variation (GCV of height and girth at 12.58% and 19.72% respectively) at seedling stage (Indira, 1999). This may be due to the representation of provenances only from Papua New Guinea. However significant differences between provenances were reported for height at 9 months old seedlings. The study also showed that provenance of Wipim performed much better, except to the Bensbach provenance, in terms of height and girth than the other provenances. It also revealed that the growth of *A. mangium* was better than the other *Acacia* species *viz. A. aulacocarpa* and *A. crassicarpa,* of different provenances at the seedling stage of 12 months. But heritability of height and collar girth of *A. mangium* appears to be low, though it is much higher than *A. crassicarpa*. Its estimated value at 12 months of growth was 0.318 and 0.21 for height and collar girth respectively, while the values of *A. crassicarpa* was estimated to be 0.014 and 0.02 for height and girth, respectively. *Acacia aulacocarpa* had the highest heritability (58% and 43% at 12 months respectively) among them for both the traits. Similarly low genotypic coefficient of variation was recorded for *A. crassicarpa* (3.19% and 6.32% for height and girth respectively) and highest in *A. aulacocarpa* (17.58% and 23.37% for height and girth respectively). Genotypic variance of height and girth for *A. aulacocarpa* decreased with age, but no particular trend existed for the other two species. On the other hand, species like *A. crassicarpa* and *A. auriculiformis* has been reported to perform much better than *A. mangium* in Thailand at six months after field establishment, where provenance evaluations of twelve *Acacia* species were done in six different locations (Pinyopusarerk and Puriyakorn, 1987). The result showed that *A. mangium* (110 cm), though not among the slowest growing species, was below the average (130 cm) at each planting site.

Many other species showed significant differences between provenances including coniferous species (Rawat and Bakshi, 2011). But one must note that though significant as it may be in terms of provenance effect in the seedling traits, it does not always imply that the increment percentage will be as significant as the provenance effect. As in case of *Sclerocarya birrea*, Dlamini (2010) reported high significant differences between provenances in seedling height and root collar diameter at five and eight months, but no significant differences were observed in percentage increment of height and root collar diameter at eight months, indicating that the best seedlings at 8 months are not necessarily the one that was growing best at five months.

Genetic effect seems to have greater role in determining the seedling height and root length. Shoot and root length for *Grewia oppositifolia* had high heritability of 75.45 percent and 80.18 percent, respectively, as well as high genotypic variance associate with the two traits i.e. 61.39 percent and 87.48 percent, respectively (Uniyal *et al.*, 2000**)**. Likewise, Takuathung *et al.* (2012) found that high genetic effect associates with height (53% to 85%) in *Senna siamea*. This is in alignment with the report of high heritability (58%) of the total variation of height of seedling of *Cordia africana*, but low heritability (3% to 13%) is associated with root collar diameter (Loha *et al.,* 2006). High genetic control and variation had also been reported in *Tectona grandis* (Jayasankar *et al.,* 1999). They recommended grading of seedlings based on their height and collar diameter at an early age as performance of the provenances in the field follow nursery growth patterns.

Study on the fifteen different provenances of *Magnolia officinalis* showed that significant difference existed among provenances in shoot length, collar diameter, number of leaves per plant, main root length and dry weights except for relative growth rate and net assimilation rate. Provenance effect contributed 93 percent of the total variation in seedling height and collar diameter. This indicates that adequate genetic variability for seedling height exists for the species and so they suggested that the traits can be used for early selection of provenance (Shu *et al.*, 2012). But no significant variation was observed for relative growth rate in the study. Low variation in relative growth rate was also reported by Takuathung *et al.* (2012) in *Senna siamea*. When relative growth rate were examined by them at three stage of development from age 2 to 6 months as first stage, 6 to 36 months as second stage and 2 to 36 months as overall third stage in *Senna siamea* high significant difference among nine provenances was found only at the first stage of development for height and diameter. This indicates that low variation associates relative growth rate.

In addition to the provenance effect, Teklehaimanot *et al.* (1998) has reported the influence of latitudinal direction on the growth performance of seedling. Measurement of morphological characteristics on four months old seedlings from five provenances of *Parkia biglobosa* grown in a tropical greenhouse under controlled conditions showed that there was wide variation between the southerly and the northerly provenances in height. Southerly provenances were taller than the northerly provenances. Such variation pattern has been reported in other species as well (Harwood *et al.,* 1997; Sebbenn *et al.,* 2003). This was in alignment with Wright (1976), who stated that southern seed-lots of same species usually grew faster compared to northern one. However, he proposed that such trends reflect only the adaptability of the species to cold and warm conditions rather than to northern and southern condition *per se*. So in case of *A. mangium*, which is adapted to warm and humid climate of tropic region, it is unlikely that the species will follow the variation trend. This is also evident from the finding of Salazar (1989). He had reported that no such relationship existed with the sites of its origin in *A. mangium*, since there were provenances which had the best growths in sites with high and low latitudes, but there is a report of other *Acacia* species, though contrary to Wright (1976), where northern provenance performed better than the southern one (Pinyopusarerk and Puriyakorn, 1987). Variations in the amount of rainfall in the seed source may also influence the growth performance of seedlings as in case of *A. karroo* (Khalil *et al.,* 2004).

2.4.4 *Field performance*

Acacia mangium is a fast growing tree species. The average annual increase in diameter, height and volume of one to seven year old plant is 2.5 cm $year^{-1}$, 2.8 cm $year^{-1}$ and 13.9 m^3 ha^{-1}, respectively and at a rotation of 5 to 7 years, the average stem volume yield is 60.7 m^3 ha^{-1} (Sein and Mitlohner, 2011). In Kerala, the average mean annual increment (MAI) at 6 and 7 years for GBH and height was 15.05 cm and 3.7 m, respectively. In the state, the species continued to grow throughout the year irrespective of seasons (Dhamodaran and Chacko, 1999). The value recorded for MAI of height (1.9 m) and diameter (2.4 cm) at 8 years for the species grown in Vietnam was much lower (Kha and Nghia, 1991). Nonetheless, it performs much better when it is compared with the performance of other *Acacia* species of the same age in the region. The mean height and diameter of the species was 15.4 m and 18.9 cm respectively, while the values of other *Acacia* species *viz. A. crassicarpa, A. auriculiformis* and *A. aulacocarpa*, ranged from 10.8 m to 13.2 m and 10.1 cm to 14.9 cm respectively. Likewise, lower MAI of height and diameter of other species ranged from 1.4 m to 1.7 m and 1.3 to 1.9 cm respectively for the latter three species. Coefficient of variation of height and diameter of *A. mangium* was only 7.9 percent and 18.2 percent respectively which was much lower than *A. auriculiformis* having 32.5 percent and 11.4 percent, respectively (Kha and Nghia, 1991).

In Malaysia, *A. crassicarpa* outperformed *A. mangium* in mean height and DBH when assessment was done at fourth year of growth for five *Acacia* species grown in four different sites (Liang and Gan, 1991). Similar finding had been reported in Tanzania (Kindo *et al.*, 2010). The superiority was most apparent in shallow, sandy soil with weeds. But in good lowland sites, the performance of *A. mangium* was comparable with *A. crassicarpa*, and much better than *A. auriculiformis* and *A. mearnsii.* Interaction between the environment (sites) and genotype (provenances) was found to be insignificant contributing only 8 percent to the total variation and combine analysis of variance for the species in the trial indicated that DBH is under greater genetic control than height (Liang and Gan, 1991). Stener and Hedenberg (2003) also reported that DBH was under stronger genetic control in *Betula pendula*. But small differences in the value of broad sense heritability of DBH and height, which is 0.46 and 0.43, respectively indicates that there is no statistical difference in the magnitude of genetic control for the two traits in *B. pendula*.

The genetic control over growth characteristics like branching, stem straightness, persistence of axis, etc. vary depending upon the species and sites. *Acacia mangium* has persistent branches as it does not naturally prune itself like *Eucalyptus* (Mead and Miller, 1991). Provenance trial of *Grewia arborea* from different geographical areas of India shows that branch thickness is strongly controlled by the environment. But mode of branching of the species is found to have moderate heritability (Indira, 2006). Stem straightness of *A. mangium* is also influenced by environment. It showed poorer form in sites with higher fertility where growth was fast. In Peninsular Malaysia, estimates of acceptable stems for sawlogs was as low as 10 percent, but in Sabah the degree of malformation was much less of a concern and there were large provenance differences in both stem straightness and the frequency of multiple leaders (Mead and Miller, 1991). The estimated genetic variance of stem straightness had been reported to be negligible in *Betula pendula* (Stener and Hedenberg, 2003) and also reported to have moderate heritability (36.5%) in *Grewia arborea* irrespective of provenances (Indira, 2006). Persistence of axis was found to be highly influence by environment for *Grewia arborea,* while the heritability of clear bole percentage and tapering was found to be high (54.6% to 61.9% for clear bole percentage and 72% for tapering). It had also been reported in *A. auriculiformis* that tapering had the highest heritability (54%) in all growth parameters and wood characteristics measured in 12 different provenances (Susanto *et al.,* 2008).

Evaluation of genetic gains by analyzing one year growth performance of height, DBH and form (stem straightness, multi-stem) traits of *A. mangium* using data collected from three second-generation orchards showed that the averages of the realized genetic gain for DBH, stem straightness, height, and multi-stem were 5.2

percent, 4.3 percent, 3.1 percent, and 0.5 percent, respectively. Except for multi-stem, performances of improved families were significantly better than those of unimproved families in three orchards for diameter at breast height (DBH) and in two out of three orchards for height and stem straightness (Nirsatmanto *et al.*, 2004).

In *Acacia* species, stability, which indicates the predictability of performance of a genotype in various environments, of height is generally greater than DBH (Liang and Gan, 1991). In the study, the stability of *A. mangium* was estimated as 0.61 and 0.75 for height and DBH respectively. On an average, it is higher than *A. auriculiformis* (0.74 and 0.19, respectively), *A. mearnsii* (0.99 and 0.13, respectively) and on par with *A. aulacocarpa* (0.58 and 0.78 respectively) but lower than *A. crassicarpa* (0.84 and 0.72 respectively). In terms of adaptability as indicated by regression coefficients, *Acacia mangium* has higher adaptability than *A. auriculiformis* and *A. aulacocarpa* in height, but in diameter it also surpasses *A. mearnsii*. The average estimated value of regression coefficients of *A. mangium* for height and DBH was 1.43 and 2.64, respectively and *A. crassicarpa* was 1.06 and 1.12, respectively while the later three species was <1 except in the height of *A. mearnsii* (2.08).

Provenance variation of *A. mangium* is high and Papua New Guinea has been reported the best provenances in many studies. Biplot analysis of fifteen provenances of *A. mangium* grown in West Java indicated that Derideri R. Morehead, Claudia River, Kini WP and Keru Village WP of Papua New Guinea are the best provenances in terms of productivity. Derideri R. Morehead provenance had the highest volume (1.10 m^3) followed by Claudia River (1.06 m^3). Correspondence analysis showed that almost all provenances were equally good in stem form. Most of the provenances fall under the second highest category of their classification i.e. straight but leaning. But different provenances showed variation in branching system. Provenances Kini WP, Keru village WP, Kiriwo/Serida WP, and Bimadebun village possessed the better branching habit. In general, five provenances i.e. Claudia River, Kini WP, Keru Village WP, Derideri R. Morehead, and Kiriwo/Serisa WP were considered appropriate for seed sources supplying seeds for industrial plantation development intended to produce construction and furniture material. The study also showed that Papua New Guinea provenances consistently performed better than Queensland (Nurhasybi *et al.*, 2009).

Provenance trials of 1 to 7 years old *A. mangium* at 19 sites in South East and South Asia, Australia and Fiji under the FAO/CSIRO-coordinated international provenance trial also revealed that, although only two provenances of Papua New Guinea *viz.* Morehead and Oriomo, is included in the trials, the performances in height, diameter and their increment was almost always better than the provenances from Queensland and Indonesia. The relative performance of Queensland and Indonesia was varied, with generally better performance of provenance of Indonesia at sites closer to the equator, but outperformed by Queensland in cooler winter climates. But in general, there is clear trend of more rapid growth of the species at sites close to the equator (Harwood and Williams, 1992). Similarly, when a range of establishment techniques were tested using different provenance of *Acacia* species in leached and degraded soils under *Imperata cylindrical* grassland in Indonesia, it was observed that *A. mangium* from Wipim provenances of Papua New Guinea had the highest growth (57 m^3 ha^{-1}) at the age of 30 months. It was 70 percent to 80 percent greater than the provenance from Indonesia (Turvey, 1996). Another investigation on genetic variation for growth traits in a composite seedling seed orchard of *A. mangium* showed that the growth of trees derived from Papua New Guinea provenance performed much better than those from Queensland provenances (Nirsatmanto, 2012). Similar finding had been reported in other studies (Harwood *et al.,* 1997; Nurhasybi *et al.,* 2009; Kindo *et al.,* 2010). In the study of Nirsatmanto (2012), despite the composite seedling seed orchard consisting of a combination of the best 10 selected plus tree families from each provenances, the differences between provenances and families within provenances for height, DBH and volume were significant, indicating an evident variation and strong genetic effect.

When compared with the performances of provenances within Papua New Guinea, provenances from the western province showed superior growth rates. Again, out of the western province, sources from the Oriomo region showed greatest promise. Of the Queensland sources the material from Claudie River in the state's far north had shown most promise and the Olive and Pascoe River provenance had been suggested as good performers in terms of form and vigor (Gunn and Midgley, 1991).

2.4 Wood properties

Wood of *A. mangium* is easy to work with all tools. It planes easily to a smooth, lustrous surface and finishes well. The nailing and screwing properties are satisfactory and the wood takes a good polish. It is resistant to termite attack via a root fungus but not entirely. It can be used for light to heavy construction materials, cabinet making, paneling, mining timbers, tool handles, etc. (Sein and Mitlohner, 2011).

Sahri *et al.* (1998) reported that physical and mechanical property of wood of *A. mangium* from Papua New Guinea provenance was better than the Queensland. Understanding such variations in wood properties is important because improvement of wood properties is the focal point in breeding program of forest tree species. But the deterrent factors is the difficulty to decide or predict what properties of wood would be desired in the future this is exacerbated by the strong influence of environment to the wood properties (Zobel and Talbert, 1984). In addition to that genetic correlations between growth and wood characteristics has been reported to be negative indicating that it is not possible to simultaneously achieve major gains in growth traits and wood traits (Susanto *et al.*, 2008).

Properties of wood vary from one species to another, within species and even in an individual tree. Differences in age and growth habitat also influence the properties of wood (Bhat *et al.,* 1985; Zobel and Talbert, 1984; Zziwa *et al.*, 2006). In *A. mangium,* age of the tree had significant effect on the moisture content, basic density and shrinkage of wood (Chowdhury *et al.,* 2005). Latitude of seed sources can also be an important factor in deciding the quality of woods of a species (Bhat and Priya, 2004; Deng *et al.,* 2014). All this parameters need to be considered while selecting a provenance for improvement in wood properties of a species.

2.5.1 Physical properties of wood

Physical properties of a wood denote such inherent qualities as the appearance, shrinkage, fiber morphology, density, etc., of wood as also its reaction of sound, heat, light, electricity, etc. **(**Shekhar, 1988).

2.5.1.1 *Moisture content*

Water constitutes about 50 percent of the fresh weight of wood (Larcher, 1995). In terms of cost for saving energy, time and money it is desirable to have low moisture content. Higher moisture content of wood makes it more susceptible to drying defects. But green moisture content of *A. mangium* is extremely high both in sapwood and heartwood. Heartwood of *A. mangium* is referred to as wet-heartwood because of its higher moisture content than that of the surrounding sapwood. The average content of moisture in the sapwood ranged from 76 percent to 149 percent and inner heartwood ranged from 57 percent to as high as 253 percent (Yamamoto *et al.,* 2003). Their studies also showed that for *A. auriculiformis,* the moisture content ranged from 57 percent to 104 percent in sapwood and 65 percent to 146 percent in inner heartwood and in *Acacia* hybrid, the moisture percentage in the sapwood ranged from 79 percent to 154 percent and 67 percent to 253 percent in the inner heartwood. Besides, the moisture content of the three species was found to be very high even in the dry season. Likewise, study conducted for moisture content of agroforestry tree species showed that *A. mangium* (49.46%) had higher green moisture content than *A. auriculiformis* (40.94%) (Shanavas and Kumar, 2006). *Acacia melanoxylon* had also been reported to have high green moisture content of 51 percent to 176 percent (Bradbury *et al.,* 2011).

Though studies indicated that *Acacia* species has high green moisture content, environment can vitiate the interpretation because of its strong influence (Bradbury *et al.,* 2011). Study conducted on 12 provenances of three year old *A. auriculiformis* in Indonesia showed that moisture content was significantly different only for family within provenances, indicating that environment had greater influence over the trait. While almost all the parameters like height, stem form, bark thickness, specific gravity, etc. investigated in the study were significantly different from one provenance to another. Heritability of moisture content for the species was found to be 0.46 and positive correlation of the trait with other growth parameters makes it appropriate to include in selection program (Susanto *et al.,* 2008). In case of *A. mangium* significant differences existed between provenances when study was conducted on four different provenances *viz.* Malaysia, Indonesia and Thailand, for physical and mechanical properties (Sahri *et al.,* 1998). Highest moisture content determined by oven dry weight method is observed in provenance of Indonesia (15.5%) followed by Thailand (13.53%) and the least from Malaysia (7.79%). Sites as well as the interaction between site and provenances were also found to be highly significant for the species. The study also revealed that the moisture content of the species is comparable with *A. auriculiformis* (12.9%).

2.5.1.2 ***Heartwood and sapwood percentage***

Cross section of wood can be divided into two types – sapwood and heartwood. The outer, paler colored wood is the sapwood and darker inner wood is the heartwood. Heartwood of *A. mangium* has brownish color which turns to dark brown when dried and they are easily distinguishable from white color sapwood. In the heartwood it has a distinct, large and loose fiber corewood forming about 7 percent to 14 percent of the wood volume which often gets detached from the rest of wood while drying (Dhamodaran and Chacko, 1999). The percentage of sapwood-heartwood is important because of its implication in production of pulp and paper. Considering the pulping quality of tree stem, heartwood is an important variable, mainly because of its high extractive content compared with sapwood, which leads to higher consumption of bleaching chemicals and lower pulp yield and brightness. This necessitates the assessment of sapwood-heartwood percentage for a species like *A. mangium* which is primarily used for pulp and paper production and the advantage of selection of such traits is that it is under strong genetic control so the interaction between the genotype and environment plays minimal role in deciding their percentage in a tree (Bradbury *et al.*, 2011; Knapic *et al.*, 2006). However, there were reports of these traits being primarily controlled by environment and that plant usually produces higher heartwood when the soil is moist and well drained (Harrison, 1974 and 1975**)**. No much work has been done to study the variations of sapwood-heartwood percentage between provenances of *A. mangium*.

Large portion of cross sectional wood of *A. mangium* is occupied by heartwood. The mean heartwood content excluding the soft core portion for 8 and 10 years old *A. mangium* ranges even up to 67.1 percent (Dhamodaran and Chacko, 1999). Lim and Gan (2011) also reported that the percentage of sapwood ranges from 5.3 percent to 17.8 percent and 11.18 percent to 25.48 percent at the age of 16 and 20 years. This is comparatively lower than the 15 years old *Eucalyptus regnans* that had average sapwood percent of 32 at the breast height (Githiomi and Dougal, 2012). The relationship between heartwood percentage and disc diameter of *Eucalyptus regnans* was found to have high correlation coefficient of 0.967, which led them to suggest that tree diameter can be effectively used to estimate the heartwood percentage of standing tree. An interesting relationship of sapwood-heartwood percentage was observed in their study where DBH showed the lowest mean sapwood width i.e. highest heartwood percentage (67.41%), but as it moves upward as well as toward the base the sapwood width increases. No such pattern of variation has been reported in most of the species studied. On the contrary, even though the area of sapwood at breast height (84.3 cm^2) was lower than at the base (102.3 cm^2), the proportion of sapwood had been reported to be greater at the breast height level in *Melia azedarach* (El-Juhany, 2011). For 20 years old *A. mangium*, the average percentage of sapwood was highest at 2.5 m (18.6%) above base and decreased as it move upward to 5 m height (17.72%) and towards the base (16.52%), but for 16 years old trees, in the same study, the percentage of sapwood was lowest at 2.5 m (9.4%) and increased in both the directions to 10.5 percent and 11.9 percent respectively (Lim and Gan, 2011). This indicated that sapwood-heartwood percentage follow no particular pattern, but greatly vary within an individual tree.

High variations ranging from 0 percent to 77 percent in the percentage heartwood has been reported for 18 year old *A. melanoxylon* (Bradbury *et al*., 2011). While, Knapic *et al.* (2006) found that large portion of the volume (61%) in the species are occupied by heartwood. The study showed that heartwood area in the stem cross-section decreased from the tree base upwards and the heartwood diameter positively correlated with the total diameter i.e. larger tree had higher heartwood. They found that on an average 69 percent of the stem cross-sectional area at the base of the tree in the species was occupied by heartwood and gradually reduced to 67 percent, 58 percent and 26 percent at a height of 15 percent, 50 percent and 75 percent of the total tree height respectively and as it reached 90 percent of the total tree height, tree was completely devoid of heartwood. This showed that the proportions of heartwood in the cross section remained stable in the lower part of the stem and as it attained 50 percent of the tree height, it decreased steadily and sharply. The lower half portion of the tree heartwood represented 66 percent of the wood volume. The height attained by the heartwood within the tree showed a tendency to increase with total tree height. Radial width of sapwood was found to be constant within the tree at an average of 31 mm up to 50 percent of total tree height, but increased to 35 mm upwards till 75 percent height level.

2.5.1.3 *Wood density*

Density of wood can be defined as the weight of a unit volume of the material and the relative density or specific gravity of a material is the ratio of the weight of the material to the weight of an equal volume of water at 4^0C (Shekhar, 1988). It is an important property of wood and positively correlates with other properties like mechanical properties, value of both fibrous and solid wood products (Pliura *et al.,* 2007). Therefore, it can be considered as reliable indicator and predictor of timber strength where no information of strength properties of wood of the species is available (Zziwa *et al.,* 2006). It is also an important parameter of raw material quality for pulping (Miranda *et al.,* 2001). From the breeding point of view, it is a desirable trait because of its highly heritable nature and responds well to genetic improvement (Zhang *et al.,* 2003; Stener and Hedenberg, 2003). There are instances when density is associated with low heritability (0.18) as in case of three years old *A. auriculiformis* (Susanto *et al.,* 2008) and moderately high heritability (0.42) in six year old *Eucalyptus dunii* (Arnold *et al.,* 2004). This may be owing to the young age of the species, because genetic influence of density increased with age (Miranda *et al.,* 2001). Heritability is also a variable character that can be influenced by environment until and unless complete genetic controls exist. Stener and Hedenberg (2003) cautioned against the use of wood density as a selection trait when the objective is to improve volume and dry matter production as their study conducted in *Betula pendula* shows negative correlation between them. Similarly, Deng *et al.* (2014) found that negative correlation exists between basic density and DBH in *Cyclocarya palirus* of different provenances, while other studies found no correlation with growth parameters and mechanical properties of a species (Bhat *et al.*, 1985; Miranda *et al.*, 2001; Bhat and Priya, 2004).

When genetic correlations between traits were tested for hybrid poplar, the genotypic correlations between weighted or minimum wood densities and stem volume or dry fiber weight were negatively moderate (-0.39 to -0.74) and significant at $P < 0.05$. Moderate to strong negative correlations between weighted wood density and tree height (-0.59 and -0.72) also existed in some sites. However, correlation between maximum wood density and growth traits were weak and not significant. Genetic gain due to direct clonal selection of weighted wood density ranges from 5.8 percent to 7.8 percent. The gained was almost half of that recorded for DBH (7.5% to 15%). Selection for DBH results in high gains in stem volume (7.4% to 13.1%), but reduction in wood density (-5.1% to -10.7%) associated with it. The reduction in the wood density (-0.6% to -5.5%) reduced, though it was still negative, when the selection was done for tree height. The largest negative effect on the gain of wood density was when direct selection was done for dry fiber weight. It decreased the gain in wood density by 2.3 percent to 3.6 percent (Pliura *et al.*, 2007).

The average basic density of *A. mangium* ranged from 464 kg m^{-3} to 623 kg m^{-3} within the age of 7 to 20 years (Dhamodaran and Chacko, 1999**;** Jusoh *et al.*, 2014**;** Lim and Gan, 2011). It was lower than *A. auriculiformis* (636 kg m^{-3}) and *A. melanoxylon* (1001 kg m^{-3}) at the age of 7 and 8 years respectively (Jusoh *et al.*, 2014; Bradbury *et al.*, 2011), but comparatively similar with *Euclayptus globulus* (430 kg m^{-3} to 486 kg m^{-3}) at the age of 8 to 10 years (Miranda *et al.*, 2001). The average basic density of *A. mangium* (464 kg m^{-3}) and *Acacia* hybrid (472 kg m^{-3}) did not differ significantly at 5 percent level, but found to be much higher than the improved second-generation of *A. mangium* (334 kg m^{-3}) derived from tree improvement program (Jusoh *et al.*, 2014). Specific gravity of green and air-dry wood of 9 to 12 year old *Acacia* hybrid (0.56 to 0.60) showed no much variation with 40 years old *Tectona grandis* (0.51 to 0.61) (Rokeya *et al.*, 2010).

Many sources of variations affect the density of wood. In *Acacia* species, it was reported that environmental influence account for more than half of the total variance (Liang and Gan, 1991). Generally, trees obtained from drier site usually have higher density than those at wetter site (Awang and Taylor, 1993). Significant site effect was also reported for average wood density and weighted wood density from four hybrid poplar clonal trials in Canada (Pliura *et al.,* 2007). Variation in density is also related to the cell size, cell wall thickness, latewood percentage of the trees (Zobel and Talbert, 1984) and latitude of seed sources (Deng *et al.,* 2014). It also varied with the relative position of the stem. When eleven species of industrial importance in Kerala were studied by Bhat *et al.,* (1985), it was found that wood density increased from base to top. Lokmal and Noor (2010) found that in *A. mangium*, radial variation of specific gravity account for 51 percent of the total variances component and the increased in specific gravity from pith to bark was reported to be about 35 percent. While in *Eucalyptus grandis*, density declined from stump level to 25 percent of tree height and then gradually increased as it move towards the upper portion of the stem (Bhat *et al.,* 1990). However, the most important source of variation that interest the breeder is the genetic/provenance effect. Provenance trial of 37 provenances of *Eucalyptus globulus* found that provenance form a highly significant source of variation for wood density and the magnitude of variation between different provenances ranged from 100 kg m^{-3} to 144 kg m^{-3}, but the interaction between the provenance and sites was negligible (Miranda *et al.,* 2001). Lokmal and Noor (2010) also reported that *A. mangium* exhibited significant variation among provenances and the provenance of Australia having specific gravity of 0.51 to 0.61 had wider range of variation than the Indonesian provenance (0.53 to 0.59). In *Casuarina* species, the performance of provenance from Indonesia varied from highest (731 kg m^{-3}) to lowest (617 kg m^{-3}) wood basic density (Kindo *et al.,* 2014).

2.5.1.4 ***Fiber morphology***

The properties of paper depend upon fiber morphology. A small fiber gives smooth surface and good opacity, while the strength increases with longer fiber (Stener and Hedenberg, 2003). Fiber length gradually increased as it moved from pith to bark (Bhat *et al.,* 1990; Quilho *et al.,* 2006). Similar observation was made for fiber diameter and fiber wall thickness. Near the pith, fiber length of *A. mangium* may be as short as 0.4 mm to 0.6 mm, which increased to as high as 1.3 mm near the bark (Honjo *et al.,* 2005). The increased in length from pith to bark in *Melia azedarach* was 0.62 mm to 0.92 mm (El-Juhany, 2011). Fiber morphology also varied with age of the tree (Quilho *et al.,* 2006; Samariha, 2011). The average fiber length of 16 years old *A. mangium* increase from 0.954 mm to 1.048 mm as it attained the age of 20 and the fiber diameter for the two age-groups was found to be at the range of 0.00 3 mm to 0.045 mm, while the lumen ranged from 0.003 mm to 0.030 mm (Lim and Gan, 2011). Bhat *et al.* (1990) found highly significant variation in fiber length with age of *Eucalyptus grandis*. The increased in fiber length from 3 to 9 years old tree was 0.81 mm to 1.15 mm. No significant correlation existed with fiber length and other growth parameters in the species except at nine years old tree with DBH and volume. The estimated coefficient of variation for fiber length at the different ages was 2.4 percent to 3.8 percent.

2.5.2 Mechanical properties of wood

2.5.2.1 ***Static bending***

The properties evaluated for static bending are useful for all engineering constructions and also in deciding suitability of species for beams, deckings, axles, wood poles, etc (Shekhar, 1988). Structural timber reflects the properties of wood stiffness measured as modulus of elasticity (MOE) and strength as Modulus of Rapture (MOR). Static bending of wood varies depending upon the position of tree stem. Modulus of elasticity decreased as it moves from bottom to top end while MOR showed no clear pattern of variation but tends to have higher value in the bottom and the top end compare to the middle portion of the stem. Modulus of rupture also varied significantly in the radial direction, however it was species dependent (Zziwa *et al.*, 2006). Static bending was also influenced by the age of the trees (Chihogo and Ishengoma, 1995). The average modulus of elasticity of 16 year old *A. mangium* was recorded as 94904.94 kg cm^{-2} in green wood grown at Johore, Malaysia and 110516.79 kg cm^{-2} for 20 year old trees grown in Pahang, Malaysia by Omar and Jamil (2011). However, they found that there was no much variation in the dry wood average MOE which was estimated at 105509.99 kg cm^{-2} and 109568.46 kg cm^{-2} for the 16 and 20 years old trees, respectively.

On the contrary, the variation in average MOR of *A. mangium* was found to be high for both the green and dry wood. At the age of 16 years, the estimated value was 810.67 and 985.04 kg cm^{-2} for green and dry respectively and at 20 years it was 1045.21kg cm^{-2} and 1132.90 kg cm^{-2} respectively (Omar and Jamil, 2011). Study at different age gradation of *Melia dubia* for wood mechanical properties also showed that it increased with age. In three year old age class the MOR was reported to be 492.60 kg cm^{-2}, this increased to 851.90 kg cm^{-2} in five year old age class. Likewise MOE increased from 52872.20 kg cm^{-2} to 68384.50 kg cm^{-2} as the tree attain its age from three to five years. Variation associated with age was attributed to the increment of annual ring, addition of more mature wood and the increased in the age of cambium as the tree grow in girth (Saravanan *et al.*, 2014).

When three important locally available fast growing tree species in Kerala were studied for their mechanical properties, it was found that *A. auriculiformis* performed better than *A. mangium*, while *Grevillea robusta* had the least performance in all the parameters studied (Shanavas and Kumar, 2006). Modulus of elasticity estimated for *A. auriculiformis, A. mangium* and *G. robusta* were 85998, 80234 and 26023 kg cm^{-2} respectively and for modulus of rupture were 733.4, 570.6 and 251.2 kg cm^{-2} respectively. In *A. mangium*, fiber stress at limit of proportionality increased significantly from inner (390.8 kg cm^{-2}) to outer position (450.7 kg cm^{-2}) along the radial direction while it remained relatively constant in all the positions for the other two species. Modulus of rupture of 9 to 12 years old *Acacia* hybrid was 734 kg cm^{-2} and 756 kg cm^{-2} and MOE was 97 kg cm^{-2} and 117 kg cm^{-2} for green and air-dry wood respectively. This was below the average of *Tectona grandis* which is estimated at 937.5 kg cm^{-2} and 125.5 kg cm^{-2} for green and dry wood respectively (Rokeya *et al.,* 2010) but higher than *A. mangium* and *A. auriculiformis*. The estimated mean MOR and MOE of *Tectona grandis* found in Kerala was 953 and 119,600 kg cm^{-2} respectively at 12 percent moisture content (Nazma *et al.,* 1981). When all the three *Acacia* species were compare with *Tectona grandis*, which is the paragon of all timber species, it showed that they had favorable strength for utilizations.

Ozhakkal (2008) also reported the influence of provenance in the static bending strength of *A. mangium*. The study conducted on different provenances of *A. mangium* in Kerala, India, showed that the MOR of Claudie River provenance (769 kg cm^{-2}) was significantly lower than other provenances including Wipim to Oriomo, Balimo Aramia which was found to have an average of 1027 kg cm^{-2} in dry condition. There was no much variation between Wipim to Oriomo (988.2 kg cm^{-2}) and Balimo Aramia (989.5 kg cm^{-2}). The performance of Claudie River provenance in the test for MOE was also found to be significantly lower than the other provenances. In wet condition the provenances showed no significant differences in both the MOR and MOE. The study also showed that *A. mangium* has lower mechanical properties compare to *A. auriculiformis*. The estimated mean value of MOR and MOE in *A.*

mangium was 975.7 kg cm^{-2} and 92763.65 kg cm^{-2}, respectively while *A. auriculifromis* had 1068 kg cm^{-2} and 94817.3 kg cm^{-2}, respectively.

2.5.2.2 *Compression strength*

Compression parallel to grains determines the suitability of species for posts, athletics and sporting goods and many other industrial purposes where forces act in direction parallel to the grain of timber or in which the loads are applied on the lateral surfaces of the timbers as in bearing surface, bolted timber, furniture, instruments, railway sleepers, some types of sports goods, etc. (Shekhar, 1988).

The average green and dry values of compression parallel to grain for 20 year old trees of *A. mangium* grown in Pahang, Malaysia was estimated to be 442.56 kg cm^{-2} and 539.43 kg cm^{-2} respectively which was higher than the 16 years old trees grown in Johore, Malaysia which had values of 366.08 kg cm^{-2} and 469.07 kg cm^{-2} for green and dry wood respectively. Similarly, the variation between the trees grown at different location was high for compression perpendicular to grain. It was estimated to be 73.42 kg cm^{-2} and 90.75 kg cm^{-2} in green and dry condition respectively for the Pahang and 55.06 kg cm^{-2} and 65.26 kg cm^{-2} respectively for the trees that were grown in Johore (Omar and Jamil, 2011). The strength of *A. mangium* for compression perpendicular to grain was lower than *Acacia* hybrid, which was estimated to be 82 kg cm^{-2} and 110 kg cm^{-2} for green and air-dry wood respectively, but higher than the estimated value of 230 kg cm^{-2} and 253 kg cm^{-2} respectively for compression parallel to grain. It was even higher than *T. grandis* in compression parallel to grain which was estimated at 288 kg cm^{-2} and 374 kg cm^{-2} in green and air-dry condition, while the compression perpendicular to grain of *T. grandis* was estimated at 82 kg cm^{-2} and 110 kg cm^{-2} (Rokeya *et al.,* 2010). The estimated coefficient of variation of *Acacia* hybrid for compression parallel to grain and perpendicular to grain was 17.73 percent and 20.33 percent, respectively at air-dry condition.

Out of the three important locally available fast growing tree species in Kerala, *A. auriculiformis* showed the highest strength of compression parallel to grain (396.6 kg cm^{-2}) and compression perpendicular to grain (77.9 kg cm^{-2}) followed by *A. mangium* (252.8 kg cm^{-2} and 77.9 kg cm^{-2}) and *G. robusta* (159.5 kg cm^{-2} and 33.6 kg cm^{-2}). In case of *A. mangium,* the compression perpendicular to grain increased from inner (61-7 kg cm^{-2}) to outer position (93.4 kg cm^{-2}), but not so in the other two species (Shanavas and Kumar, 2006).

Differences in compression strength of wood can also arise due to differences in the age because mechanical properties increase with age. This is evident from the finding that compression strength parallel to grain and perpendicular to grain was found to be increased from 241 kg cm^{-2} to 283.30 kg cm^{-2} and 31.80 kg cm^{-2} to 104.20 kg cm^{-2} respectively as the age class increased from three to five years old in *Melia dubia* (Saravanan *et al.,* 2014).

MATERIALS AND METHODS

3. MATERIALS AND METHODS

The present study on "Provenance evaluation of *Acacia mangium* Willd. for growth and wood traits" was conducted to evaluate the variations that exist in growth and properties of wood of different provenances of *Acacia mangium* grown in humid tropic conditions of Kerala, India. The detail of the materials and methods are explained hereunder.

3.1 MATERIALS

3.1.1 Geographic location and climate of the study area

The present field trial was carried out on a pre-existing provenance evaluation trial on *A. mangium.* The trial plantation was established during the year 2000 under the All India Co-ordinated Research Project on Agroforestry (AICRPAF; Plate 1). It was located at Livestock Research Station, Thiruvazhamkunnu ($11^0$21' N, $76^0$21' E) in Palakkad district of Kerala, India. The elevation of the site is approximately 60 m above mean sea level. The place experiences warm, humid tropical climate and high rainfall. The average annual rainfall ranged from 2600 mm $year^{-1}$ to 3200 mm $year^{-1}$ (AICRPAF, 2005 – 2013). Most of the rainfall is received during the southwest monsoon season i.e. June to August, with secondary peak in September to October. Soil of the experimental site is ultisol with an average pH of 5.4 and bulk density of 0.86 g cm^{-3} (Kunhamu *et al.*, 2010).

3.1.2 Seed source

The experimental materials comprised of ten provenances and one local seed source (Kerala). Out of the ten provenances, six were from Papua New Guinea and four from Queensland, Australia. All of the seed lots obtained from the ten provenances were from within the range of natural distribution of the species. The seeds were obtained from the Australian Tree Seed Centre, CSIRO, Australia. Seeds

Plate 1. (A) A view of the trial plantation. (B) Closer view of the plantation with trees arranged in 3 m × 3 m spacing.

of the local seed source were collected from trees whose parents were unkown. The details of provenances of the seed lots and local seed source are given in Table 1.

Table 1. Details of the seed lots of *A. mangium* provenances used in the provenance trial.

Seed lot No.	Locality	Region	Latitude (S)	Longitude (W)	Alt. (m)
17703	Tully-Mission Beach	Queensland	17^0 33’	146^0 3’	20
18206	Arufi Village WP	Papua New Guinea	8^0 25’	141^0 33’	25
19619	Claudie River	Queensland	12^0 28’	143^0 10’	20
19678	Oriomo WP	Papua New Guinea	8^0 29’	143^0 00’	10
19761	Kuranda	Queensland	16^0 29’	145^0 22’	0
20045	Pascoe River	Queensland	12^0 20’	143^0 5’	20
20127	Lake Murray	Papua New Guinea	7^0 0’	141^0 19’	50
20128	Balimo	Papua New Guinea	8^0 3’	142^0 34’	15
20130	Upper Aramia	Papua New Guinea	7^0 33’	142^0 21’	15
20134	Binaturi	Papua New Guinea	9^0 0’	141^0 32’	20
-	Thiruvazhamkunnu	Kerala	12^0 21’N	76^0 21’ E	65

3.1.3 Experiment design

The experiment was laid out in randomized complete block design (RCBD) with eleven provenances as treatment laid out in three replications. Trees were planted at 3 m × 3 m in a total plot size of 225 m^2 such that each experimental plot had 25 trees. In total, there were 33 such plots (11 provenances × 3 replications). For establishing the plantation, three months old poly bag seedlings grown in nursery were used.

3.2 METHODS

3.2.1 PART I

3.2.1.1 Estimation of height, girth at breast height and volume of trees

The present study for evaluation of growth attributes for the provenances was conducted during the 14th year of establishment of the provenance trial. Biometric attributes of the provenances were measured from all the trees of each replication, excluding the border trees, such that there were net nine trees available for measurement in each experimental plot. Total height and clear bole height of the individual tree was measured using Vertex Laser hypsometer (VL402) set at three points height for straight trees and two points laser height for leaning trees. The pivot offset of the device was set at 0.3 m and angle unit set as degrees. After the settings, the instrument was allowed to adjust with the current working temperature for at least 10 minutes. Readings of height were then taken from the tip of the leading shoot of tree. Forking below the girth at breast height (GBH) was considered as separate trees and enumerated separately. Clear bole height was measured at the point where first crown forming living or dead branch was formed and the proportion of clear bole height to the total height were expressed as percentage. Girth was measured at breast height (1.37 m) above ground using measuring tape. Whenever there was abnormality at 1.37 m, GBH were measured by shifting up or down as little as possible to a more normal position of the stem.

Tree volume over bark of each tree were calculated using the following formula

$$\text{Tree volume (m}^3\text{)} = \pi \times \frac{DBH^2}{4} \times H \times F$$

Where,

DBH = diameter at breast height.

H = total height of the tree

F = form factor (0.65)

The calaculated mean tree volume for each experimental plot was multiplied by the number of trees per hectare (1111 trees ha^{-1}) to arrive at stand volume per hectare.

Mean annual increment (MAI) in DBH was estimated using the secondary data of 10 years (2005 to 2014) collected by AICRPAF. The data of only the surviving trees by the time when measurement was carried out in 2014 were used and those trees that were dead were excluded from all the years for estimating the MAI.

3.2.1.2 Estimation of tree form characters

Tree form characters considered in the present study were persistence of stem axis, straightness of stem and stem taper. For estimating the tree form characters of the provenances of *A. magium*, each tree was assessed using visual scoring system as given by Indira (1999). The score was assigned in such a way that high value would correspond to a positive or better characteristics compared to the lower score value.

3.2.1.2.1 *Persistence of stem axis*

For estimating the persistence of stem axis, the total height of tree was divided into four quarters. In addition to division of the tree into four quarters, two more classes (1 and 6) were added and scoring were followed as under

Score 1 – Tree is multiple stemmed at the ground level
Score 2 – Main stem branched out in the lowest quarter
Score 3 – Main stem branched out in second quarter
Score 4 – Main stem forked in the third quarter
Score 5 – Main stem forked in the fourth quarter
Score 6 – Complete persistence of axis

3.2.1.2.2 *Straightness of stem*

Stem straightness of each tree was scored using five point scales as

Score 1 – Trees with crooked and more than three serious bends
Score 2 – Trees crooked and with 1 or 2 serious bends
Score 3 – Trees slightly crooked with many bends
Score 4 – Trees slightly crooked and with few bends
Score 5 – Straight trees

A bend is defined as the distance between two tops of a stem and if the side of the stem curves outside a straight line (imaginary axis) drawn through the length of a bend (Figure 1) or if bends can be recognized at breast height, it is considered as serious (Keiding *et al.,* 1986).

3.2.1.2.3 *Tapering*

Taper of a tree is the decrease in diameter of stem of the tree from base upwards. To estimate the taper of tree, girth at 7 m above ground level was measured using measuring tape for all the trees of the provenances (excluding border trees). The taper was calculated using the formula given by Indira (2006) with slight modification by taking at 7 m above the ground level.

$$\text{Taper} = \frac{\text{Girth at 7 m height}}{\text{Girth at 1.37 m height}}$$

3.2.1.3 Branching habit

Branching habit which is an important factor that influenced competition, productivity and economic values of the tree were estimated for the provenances using scoring system as given by Indira (1999). Branching habits estimated for each tree in the present study were branch thickness and mode of branching.

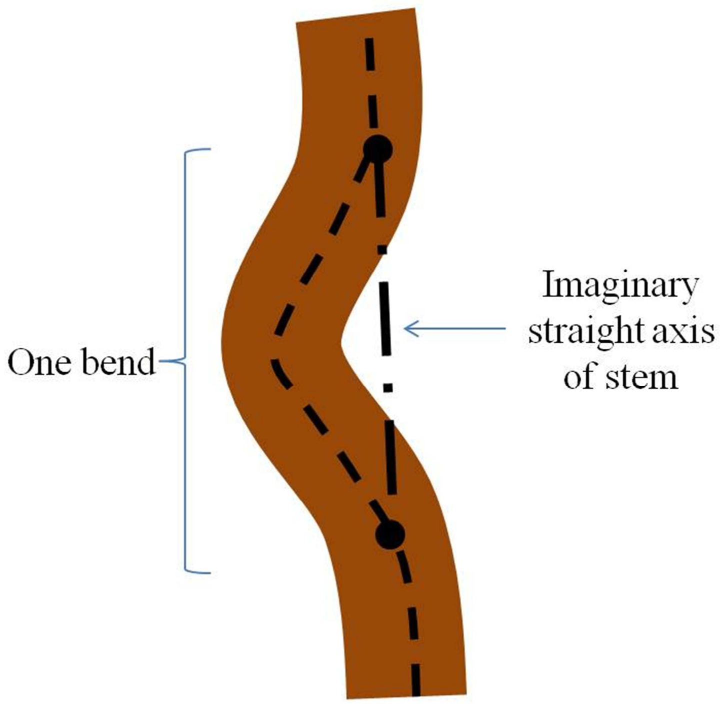

Figure 1. Pictorial representation of serious bend of stem axis.

1.2.1.3.1 *Branch thickness*

For branch thickness five classes were identified and scored as

Score 1 – Tree with heavy branches of more than half the size of the main stem

Score 2 – Tree with heavy branches of half the size of the main stem

Score 3 – Trees with medium branches with one fourth to half the size

Score 4 – Tree with light branched trees with one fourth size of the main stem

Score 5 – Tree with light branched trees with very light branches with less than one fourth size of the main stem.

3.2.1.3.2 *Mode of branching*

Mode of branching was also allotted into five classes as given below

Score 1 – Tree with double limbs

Score 2 – Tree with scattered but pronounced branching

Score 3 – Tree with light forking

Score 4 – Tree with scattered but light branching

Score 5 – Tree with very light branching

3.2.2 PART II

3.2.2.1 Progeny evaluation in the seedling stage

In the present study, morphometric traits of seeds, seed viability and seed germination related parameters were included under this section. The performance of seedlings in terms of height, collar girth and relative growth rate of the different provenances of *A. mangium* were evaluated in the nursery.

3.2.2.1.1 *Collection of seeds*

For progeny testing, seeds were collected from the trial plantation during the month of March, 2014. The seeds were collected from open pollinated trees. Pods that were fallen on the ground were collected replication wise from each treatment plot for extraction of seeds (Plate 2). In order to avoid contamination of seeds from nearby plot of different provenance, the pods that were fallen on the border of the plots were discarded. After collection, seeds were extracted manually from pods, cleaned and air dried. The dried seeds were bulked provenance-wise and stored in air-tight polythene bag, with a zipper at room temperature.

3.2.2.1.2 *Measurement of morphometric traits of seeds*

The morphometric traits of seeds estimated in the present study were seed length, width, thickness and weight. For estimating the morphometric traits, 100 seeds were drawn from the composite sample of each provenance and allotted 25 seeds each to four replicates. Proper measures were taken to avoid contamination. Length, width and thickness of individual seed were measured using digital vernier caliper. Measurements were taken at the longest, widest and thickest axis of seeds. During the measurement, shriveled and damaged seeds were discarded.

3.2.2.1.3 *Viability of seed*

Tetrazolium test was used for testing the viability of seeds of the provenances. Tetrazolium solution (0.3%) was prepared by dissolving 2,3,5-triphenyl tetrazolium chloride (TTC) in distilled water in a flask which was covered with paper to avoid penetration of light. Prior to the test, seeds were pre-treated by soaking them in water overnight. Thirty seeds were drawn after discarding the damage and floating seeds. Seed coat at the distal end of the selected seeds was then decoated manually using scalpel. This was done in order to facilitate penetration of solution to the seed. The decoated seeds were then placed in the TTC solution in petri dish and kept in the oven at 30^0C for 24 hours (Purohit and Bisht, 1999). During the process, precautionary measures were taken to prevent interaction of the solution with light. After soaking for 24 hours, seeds were removed from the oven and the cotyledons of the treated seeds were carefully separated using a scalpel and examined under magnifying glass (10X).

Based on the staining pattern, the viable and non-viable seeds were categoriezed as suggested by Purohit and Bisht (1999). The staining patterns of seeds and its categorization are described in Table 2.

3.2.2.1.4 *Dormancy and germination test*

Germination tests for the provenances of *A. mangium* were carried out during the month of June, 2014. For testing the germination, four replicates of 25 seeds from each of the provenances and local seed source were immersed in hot water at 100 ^{0}C in 10 times the volume of seeds for 30 seconds and subsequently, they were soaked in cold water for 24 hours (Bowen and Eusebio, 1981). Additionally, 20 seeds from each provenance were randomly selected and bulked to draw 100 seeds to use as control. The control seeds were soaked in cold water for 24 hours prior to germination test. Seed weights were measured from each replication by weighing the seeds before and after the treatment of seeds for germination and soaking in cold water to an accuracy of 0.1 mg. From the measurement of weight at different stage, the amount of water absorbed was determined as the actual increase in seed mass and expressed in percentage.

$$\text{Percentage increase in mass} = [(W_{im} - W_i) / W_i] \times 100$$

Where,

W_{im} = mass of water imbibed seeds in mg

W_i = initial mass of dry seeds in mg

Table 2. Descriptions of staining pattern of viability of seeds and its categorization into viable or non-viable seeds (Purohit and Bisht, 1999).

Sl. No.	Description	Categories
1	Embryo and cotyledons completely stained	Viable seed
2	Embryo completely stained and cotyledons ¾ stained	
3	Embryo completely stained and cotyledons ½ stained	
4	Embryo completely stained and cotyledons stained except for occasional small unstained patches here and there	
5	Embryo completely stained and ¼ cotyledons near embryo stained	
6	Embryo completely stained and ¼ cotyledons surrounding embryo unstained	Non-viable seed
7	Embryo completely stained and cotyledons unstained or stained in occasional patches	
8	Embryo unstained and cotyledons ½, ¾ or completely stained near embryo	
9	Embryo more than ½ unstained and cotyledons ½, ¾ or completely stained	
10	Embryo and cotyledons unstained	

After the measurement of seed weight, seeds were placed in petri dishes fitted with two layers of Whatman No. 1 filter paper moistened with 4 ml distilled water and incubated in chamber at a temperature of 30^0 C (plate 3). The filter paper was kept moist throughout the study period. Germination was recorded everyday for 27 days and seed was considered as germinated when the radicle was visible. The germination related parameters were computed as follow (Panwar and Bhardwaj, 2007)

$$\text{Germination percentage} = \frac{\text{Total number of seeds germinated}}{\text{Total number of seeds sown in all replications}} \times 100$$

$$\text{Germination capacity} = \frac{\text{Total seeds germinated} + \text{seeds found viable at end of test}}{\text{Total number of seeds sown in all replicates}} \times 100$$

$$\text{Germination energy} = \frac{\text{Total seeds germinated up to the time of highest number of germination in a particular day}}{\text{Total number of seeds sown in all replicates}} \times 100$$

$$\text{Germination value} = \text{Final MDG} \times \text{Peak value}$$

Where,

MDG = mean daily germination

$$= \frac{\text{Cumulative percent of seed germinated at the end of the test}}{\text{Days since sowing to end of the test}}$$

$$\text{Peak value} = \frac{\text{Cumulative germination percent}}{\text{Days since sowing}}$$

$$\text{Cumulative germination percent} = \frac{\text{Cumulative total}}{\text{Total number of seed sown}} \times 100$$

Plate 2. (A) Pods of *A. mangium*. (B) Seeds of *A. mangium* with orange folded funicle.

Plate 3. Germination test of seeds in an incubation chamber.

Germination period = the number of days for 80 percent or more germination from the total number of germinated seeds.

Impermeability of seeds is the major contributing factor for physical dormancy. In order to study the nature of dormancy, the permeability of seeds were studied by comparing the data collected from the increase in mass of the seeds that were treated with hot water and seeds that were soaked only in cold water for 24 hours (control), as well as by comparing with the germination percentage of the treated seeds and control seeds.

3.2.2.1.5 *Seedling growth*

For studying the seedling performances of the provenances, seedlings were raised in the nursery located at College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur. The experiment designed was RCBD with four replications.

Hundred seeds were drawn from the bulked sample for each provenance and they were sown by broadcasting on sand filled tray. The sown seeds were then covered with 3-5 mm layer of fine sand and allowed to germinate. The trays were kept moist throughout the study period. After the germination and when the seedlings had about three leaves and 3 cm to 5 cm tall (Plate 4), they were pricked out and transplanted to a polybag filled with potting mixture of sand, soil and manure at a ratio of 2:1:1 (Plate 5). The work was carried out approximately after 33 days of sowing and during the month of July, 2014. The transplanted seedlings were then placed under shade net for one month before exposing to full sunlight. Regular irrigation and weeding were done (Plate 6). No fertilizers were applied to the seedlings during the study period.

For measuring height and collar girth, five seedlings from each replication were randomly selected and measured using ruler and caliper. The observations were initiated after 50 days of transplanting in the polybags. In order to measure height of

Plate 4. Germination of seeds sown on sand filled tray.

Plate 5. Transplanting of seedlings.

Plate 6. Irrigating the seedlings of the provenances.

the seedlings, the ruler was carefully adjusted at the surface of the potting mixture and height was recorded from tip of the leading shoot of seedling. Collar diameter was measured at the base of the shoots just above the surface of the potting mixture. Measurement was done at an interval of 30 days.

For measuring the relative growth rate (RGR), three seedlings from each treatment of a replication were randomly selected and extracted. They were carefully washed in a running tap water so as not to damage the root systems. After washing, seedlings were dried for few minutes. Soon after drying, the seedlings were separated into shoot, root and leaves and their fresh weight recorded. Shoot length, root length and collar diameter were measured using ruler and caliper. The measured parts were then placed in a paper bag and transferred to an oven and kept at a temperature of 80 ^{0}C till constant weight was achieved for measuring dry weight. This method of destructive sampling was carried out at an interval of 30 days starting from August till December.

Relative growth rate was determined as described by Hoffmann and Pooter, (2002).

$$\text{RGR} = \left[\overline{\ln(\text{W}_2)} - \overline{\ln(\text{W}_1)}\right] / (t_2 - t_1)$$

Where,

W_1 = dry weight at time t_1

W_2 = dry weight at time t_2

$\overline{\ln(W_t)}$ = mean of the ln-transformed plant weight at time *t*.

3.2.3 PART III

3.2.3.1 Selection of tree and felling

After taking the readings of biometric attributes from the standing tree, volume of each tree were computed and one tree from each treatment plot having a volume equal to or nearest to the average tree volume of the treatment plot and devoid of any visible defects or infections were identified as representative tree and marked for felling.

Before felling the trees, position of breast height (1.37 m) and north-south direction were marked on each selected tree. Trees were then felled using power chain-saw. Total of 33 trees (11 provenances/local seed source × 3 replications) were thus marked and felled. Felling was carried out at the best possible way to cut the trees at the basal portion nearest to the ground level and with extreme care to avoid or cause mnimum damage to the adjacent trees (Plate 7). After felling, total height was measured using measuring tape followed by marking at 0.5 m above and below the DBH to obtain a billet of one meter length. Marking was also done at 10 percent (base), 50 percent (middle) and 75 percent (top) of the total height of the tree and from this portion 10 cm transverse disc were obtained to study the variation in physical properties of wood, while one meter billets were used for studying mechanical properties. Further conversions of the discs and billets into standard sample size were carried out in the saw mill (Plate 8).

3.2.3.2 Physical properties of wood

The 10 cm transverse discs collected at different height of the felled trees were cut into two transverse discs of approximately 6 cm and 4 cm thickness. The thinner disc was used for estimation of heartwood percentage and the thicker disc was used for determining basic density and fiber morphology. Fiber morphology was studied

Plate 7. Felling of trees using power chain saw and cutting into billet and disc (inset).

Plate 8. Further conversion of billets and discs into standard sample size in saw mill

only from the disc obtained from the base of the tree, while basic density was estimated from the discs obtained from all the height levels.

3.2.3.2.1 *Heartwood percentage*

To determine the heartwood percentage, one side of the 4 cm transverse discs was cleared of dirt and other particles and the diameter of the minor and major axis of the disc were first marked using a marker and ruler. The radii in four directions of the disc and heartwood as marked on the disc were then measured using ruler (Plate 9). The proportion of the area of heartwood of each radius from the total area of the disc was estimated using the formula given below and the average was taken as the heartwood percentage of the disc (Lim and Gan, 2011)

$$\text{Heartwood percentage} = \frac{r^2}{R^2} \times 100$$

Where,

r = radius of the heartwood

R = radius of the disc under-bark

3.2.3.2.2 *Basic density*

For estimating basic density, transverse disc of 6 cm thickness obtained from different height levels were further converted into small rectangular block size of 2 × 2 cm in cross-section and 6 cm in length conforming to the IS: 1708 (Part 2) of BIS (1986). Four rectangular specimens were randomly obtained from each disc and soaked in distilled water for 24 hours so that it attained green volume condition. Green volumes of the blocks were then determined using water displacement method (Plate 10). The specimens were then oven-dried at 103 ± 2^0C till it attained constant weight. They were weighed using precision balance with accuracy of 1.0 mg and basic density was calculated as given by BIS (1986).

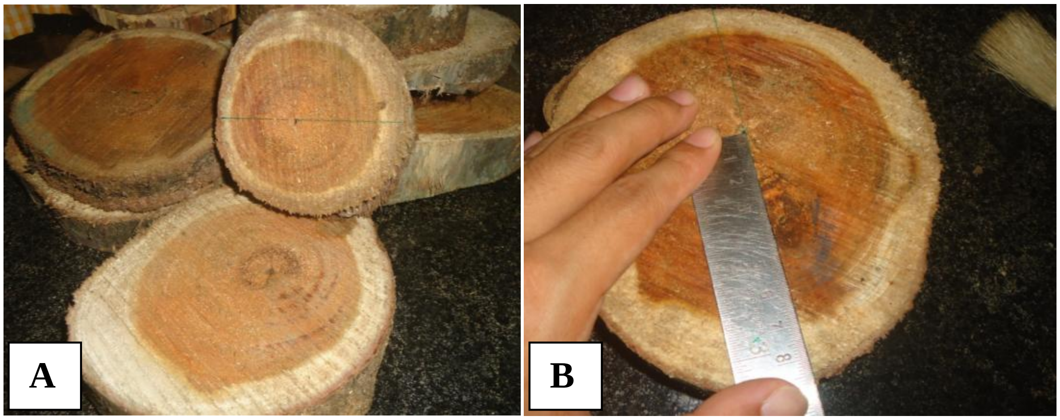

Plate 9. (A)Transverse discs from different height levels. (B) Measuring the heartwood radius using ruler

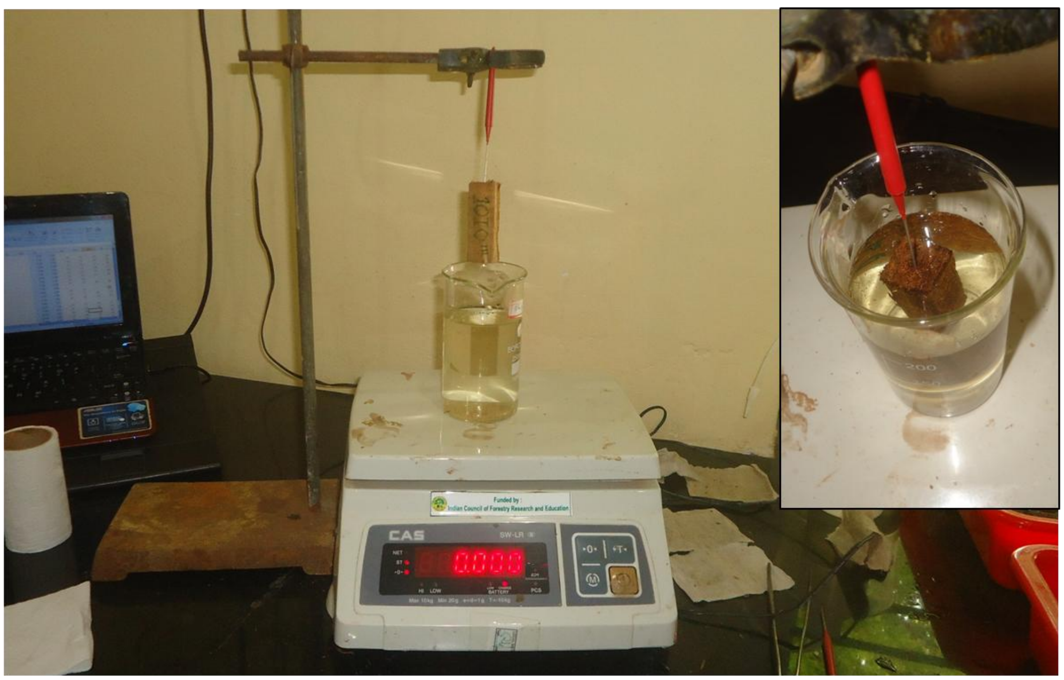

Figure 10. Measuring green volume of wood sample using water displacement method.

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

3.2.3.2.3 *Fiber morphology*

For studying fiber morphology, four rectangular wood blocks from each felled tree were obtained from the base of the tree height. The blocks were randomly selected from the disc. From each block, wood slivers that were sliced parallel to the grain were obtained using a scalpel and they were mixed together (Plate 11). From the composite, sufficient quantity of slivers were obtained and macerated using Jeffrey's method (Sass, 1971). Jeffrey's solution was prepared by mixing potassium dichromate (10%) and nitric acid (10%) in distilled water. The slivers were boiled in the maceration fluid for 15 to 20 minutes so that the individual fibers were separated (Plate 12). After boiling, fibers in the solution were allowed to settle at the bottom for 5 to 10 minutes (Plate 13). Then the solution was discarded and the remaining fibers were thoroughly washed in distilled water several times until traces of acid were removed (Plate 13). The macerated fibers were then placed in watch glass. For staining, few drops of saffranin dye were added and left for at least 5 minutes. Macerated dyed fibers were than mounted on temporary slides using glycerin as the mountant.

The macerated dyed fibers were examined and quantified using an Image Analyzer (Labomed DigiPro-2). Fiber diameter and lumen width were measured with a magnification of 40X object lens and the fiber length was measured with a magnification of 10X object lens. Twenty five randomly selected fibers were analyzed for each provenance from a replication. Fiber wall thickness was calculated by deducting the lumen width from the fiber diameter.

Different indices which are important in pulp and papermaking were derived from the data obtained using the following formulae:

$$\text{Runkel Ratio} = \frac{2 \times FWT}{L}$$ (Okereke, 1962)

Figure 11. Slivers obtained from rectangular block of the disc.

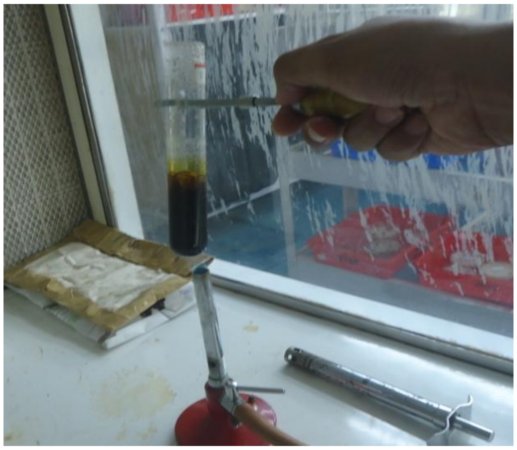

Figure 12. Maceration of slivers using Jeffrey's method.

Plate 13. Allowing the macerated fiber to settle down. The test tubes with clear solution are ready for extraction of fiber.

Slenderness ratio $= \frac{Fl}{FD}$ (Varghese *et al*, 1995)

Rigidity coefficient $= \frac{2 \times FWT}{FD} \times 100$ (Dutt and Tyagi, 2011)

Flexibility coefficient $= \frac{L}{FD} \times 100$ (Wangaard, 1962)

Where,

FWT = Fiber wall thickness

Fl = Fiber length

L = Lumen width

FD = Fiber diameter

3.2.3.3 Mechanical properties of wood

Mechanical properties of wood were determined on a 50 kN capacity Universal Testing Machine (Model: Shimadzu, Japan) in air-dried samples (Plate 14 and 15) and the tests were conducted only for five randomly selected provenances *viz.* Arufi Village, Claudie River, Kuranda, Upper Aramia and Kerala seed source.

3.2.3.3.1 ***Preparation of test samples***

One meter billets obtained from the basal portion of the stem were used for assessing mechanical properties of wood. Scantling of size 5 cm × 5 cm cross section and 1 m in length were cut from the logs in green condition. These scantlings were further converted into standard small clear specimens for different test as per Bureau of Indian Standards (1986) (IS: 1708). From the converted small clear specimens of each log, two samples corresponding to north and south directions were taken for each test.

Plate 14. 50 kN capacity Universal Testing Machine (Shimadzu, Japan).

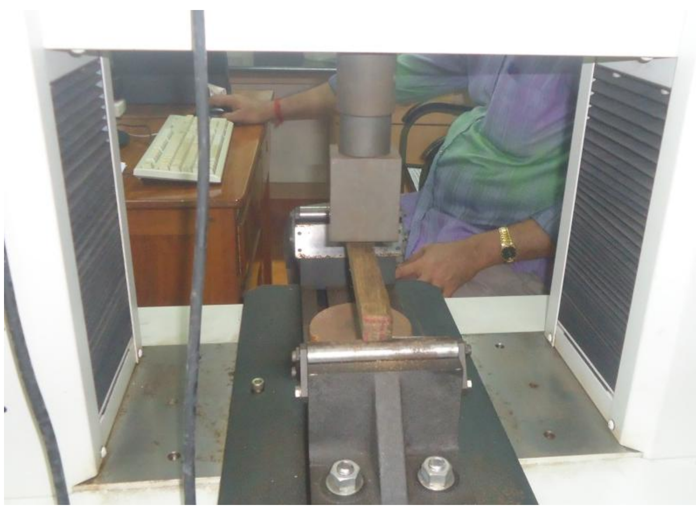

Plate 15. Sample loaded for testing the static bending strength.

3.2.3.3.2 ***Static bending tests***

For testing the static bending strength, the scantlings were converted into a sample of size 2 cm × 2 cm cross section and 30 cm in length. The bending test for the samples was then conducted with a 280 mm span in the machine. Before loading the samples for testing, the width and thickness were accurately measured. The specimen with its tangential surface was centre-loaded and the displacement controlled rate was set at 1.0 mm min^{-1} as per the BIS (1986) (IS: 1708). Load by deflection curve was recorded from the monitor. The parameters *viz.* modulus of elasticity (MOE) and modulus of rupture (MOR) were recorded.

Reanalysis of the derived data was done to calculate MOE accurately. The software calculated MOE over a range of deflection at limit of proportionality. To overcome this discrepancy, the tangent of the curve was adjusted to the maximum and deflection corresponding to the proportionality limit was recorded. Than the parameters were analyzed by substituting the value obtained in the following formulae (BIS, 1986)

$$\text{Modulus of rupture (kg cm}^{-2}\text{)} = \frac{3\,Pl}{2\,bh^2}$$

$$\text{Modulus of elasticity (kg cm}^{-2}\text{)} = \frac{Pl^3}{4\Delta\,bh^3}$$

Where,

P = load in kg at the limit of proportionality

l = span of the test specimen in cm

b = breadth of test specimen in cm

h = depth of the test specimen in cm

Δ = deflection in cm at the limit of proportionality

3.2.3.3.3 ***Compression strength parallel to grain***

All the test procedures followed for testing the compression strength parallel to grain were in compliance with the BIS (1986). The scantlings of size 5 cm × 5 cm cross section were converted into sample size of 2 cm × 2 cm cross section and 8 cm in length for testing the compression strength. Proper care was taken during the preparation of sample so that the ends of the rectangular test specimen were smooth, parallel and normal to the axis. Before the test, the dimensions were recorded accurately as specified and the samples were subjected to displacement controlled rate of 0.6 mm min^{-1}. The sample was loaded with its longitudinal axis along the direction of movement of head so that the directions of grains were in parallel to the direction of force and the movable head was vertically above the centre of the cross-section of the specimen. Load-deflection curve was analyzed through the reanalysis mode. A tangent was drawn in such a way that maximum number of points are in the straight line. Compressive stress at maximum load (MCS) were then determined as follow (BIS, 1986)

$$\text{Maximum compressive stress (kg cm}^{-2}) = \frac{P}{A}$$

Where,

P = maximum crushing load in kg

A = cross sectional area of specimen in cm^2

3.2.3.4 Estimation of genetic parameters

Genetic coefficient of variation (GCV) and environmental coefficient of variation (ECV) were computed for all the parameters under study and they were established as variability indicators to understand the magnitude of variation due to provenance and environment. In order to determine the coefficient of variations and heritability, the variance components derived from the ANOVA table were used. Genetic advance (GA) was estimated at 5 percent selection intensity.

The components of variance i.e. provenance/genotypic variance ($\sigma^2 g$), environmental variance ($\sigma^2 e$) and phenotypic variance ($\sigma^2 p$) were determined from ANOVA using the following formulae (Lauridsen *et al.*, 1987)

$$\sigma^2 g = (MSP - MSE)/r$$

$$\sigma^2 p = MSP/r$$

$$\sigma^2 e = MSE/r$$

Where, *MSP*, *MSE* and *r* are the mean squares of provenance, mean squares of error and number of replication, respectively.

Genotypic coefficient of variation and environmental coefficient of variation were determined using the following formulae

$$\text{GCV} = \frac{\sqrt{(\sigma^2 g)}}{\text{overall mean}} \times 100$$

$$\text{ECV} = \frac{\sqrt{(\sigma^2 e)}}{\text{overall mean}} \times 100$$

To determine the contribution of genetic to the total variation, broad sense heritability (H^2) was determined. Variance components obtained from analysis of individual tree measurements were used to estimate the broad sense heritability of a trait. It was calculated as the ratio of expected mean square of the genetic variance ($\sigma^2 g$) to the total variance ($\sigma^2 g + \sigma^2 e$) as follows.

$$H^2 = \frac{\sigma^2 g}{\sigma^2 g + \sigma^2 e} \times 100$$

Genetic advance (Gs) was determined as (Burton and Devane, 1953)

$$Gs = i\sigma_p H^2$$

Where, i = selection intensity at 5 percent level (2.06)

σ_p = phenotypic standard deviation

H^2 = heritability of the trait

The expected genetic gain in percentage of mean was than calculated as (Burton and Devane, 1953)

$$\text{Genetic gain} = \frac{Gs}{overall\ mean} \times 100$$

The coefficient of variations, heritability and genetic gain were classified as suggested by Sivasubramanian and Madhavamenon (1973) and Johnson *et al.*, (1955) as in Table 3.

Table 3. Classification of genetic parameters

Genetic parameter	Low	Moderate	High	Reference
GCV and ECV	0 to 10%	10 to 20%	> 20%	Sivasubramanian and Madhavamenon, 1973
Genetic gain	0 to 10%	10 to 20%	> 20%	Johnson *et al.*, 1955
Heritability	0 to 30%	30 to 60%	> 60%	Johnson *et al.*, 1955

3.2.4 Statistic analysis

Statistic analysis were done using IBM SPSS statistic 20.0. In order to perform univariate analysis to compare the effect of provenances in all the parameters under study, dependent variables were empirically investigated to check the fulfillment of the assumption of normality. The limit of skewness and Kurtosis for qualifying the assumption was fixed at |2| and |9| respectively (Schmider *et al.*, 2010). Levene's test was conducted prior to the analysis to test the homogeneity of variance. Data not normally distributed were transformed using appropriate transformation procedure. If the univariate analysis showed statistically significant difference between provenances, it was followed by post-hoc comparisons using Duncan Multiple Range Test (DMRT).

Being a nominal scale for the score obtained for tree form (persistence of axis and straightness) and branching habit (branch thickness and mode of branching), the data were analyzed using Friedman test. But, univariate analysis were followed for the percentage of good axis persistence, straightness and light branched trees and the ANOVA obtained were further used for analyzing the genetic parameters of the provenances.

In order to analyze the stability of the provenances in growth and the interaction of the different genotypes with the environment, the secondary data collected for the ten year periods of MAI of DBH were analyzed in R (Version 3.2.2) using Additive Main Effects and Multiplicative Interaction Model (AMMI) from the package Agricolae. The biplot graphic interpretation obtained from the analysis was based on the variation caused by the main effects of genotype and environment, as well as the multiplicative effect of the genotype × environment interaction (G × E interaction). The lower the interaction principal component analysis (IPCA) indicates the lower its contribution to the G × E interaction (Silveira *et al.*, 2013).

Pearson correlation was used for testing the inter-correlation between morphometric traits of seeds, germination related parameters and seedling growth as well as between the growth traits and wood properties.

Clustering of the provenances was done using six traits *viz.* height of the 14 year old trees, heartwood content at the base, average basic density, fiber length, fiber wall thickness and fiber diameter, which are significantly different between the provenances. Hierarchical cluster analysis was performed using Ward's method. For each cluster, the means for all variables were calculated and the squared Euclidean distance was measured for each case. Since the clustering was done on different scale, transformed values was standardize to Z scores by variables.

RESULTS

4. RESULT

4.1 PART I

4.1.1 Height, DBH and volume of trees

Height, DBH and volume were empirically investigated to evaluate the variation in growth attributes among the provenances of 14 years old *A. mangium* and the results of the analysis are summarized in Table 4. Since, the volumes of the provenances were found to deviate from normality, logarithmic transformation was done prior to statistical analysis.

Table 4. Variation in mean height, DBH and volume of the provenances of *A. mangium* grown in Thiruvazhamkunnu at 14th year of growth.

Provenances	Height (m)	DBH (cm)	Volume (m^3 ha^{-1})
Tully-Mission Beach	18.61^{cd}	18.20	401.03
Arufi Village WP	21.36^{ab}	20.86	668.80
Claudie River	17.97^{c}	18.02	463.11
Oriomo WP	19.83^{abcd}	20.84	567.93
Kuranda	22.12^{a}	20.60	589.16
Pascoe River	18.33^{c}	17.89	412.74
Lake Murray	18.75^{bcd}	17.98	443.49
Balimo	19.58^{abcd}	18.88	515.86
Upper Aramia	21.27^{abc}	20.45	638.20
Binaturi	19.54^{abcd}	17.36	398.42
Kerala	19.06^{bcd}	18.90	427.66
Overall mean	19.67	19.13	504.59
P	0.003*	0.204^{ns}	0.053^{ns}

Mean values with similar superscript along the column do not differ significantly
*significant at 5 percent level and superscript ‘ns’ indicate non-significant.

Analysis of height showed significant differences between provenances. The overall mean height of the provenances was 19.67 m. The mean height of the provenances ranged from 17.97 m to 22.12 m. Kuranda provenance showed the best performance (22.12 m). However, provenances of Arufi Village (21.36 m), Upper Aramia (21.27 m), Oriomo (19.83 m), Balimo (19.58 m) and Binaturi (19.54 m) were on par with Kuranda provenance. The provenances that performed the least in height in the present study were Claudie River (17.97 m) and Pascoe River (18.33 m). However, the two provenances were significantly different only from Arufi Village and Kuranda provenances.

Diameter at breast height and stand volume did not differ significantly between the provenances. The overall mean of DBH and volume were 19.13 cm and 504.59 m^3 ha^{-1}, respectively. Diameter at breast height of the provenances varied from 17.36 cm to 20.86 cm and the volume ranged from 398.42 m^3 ha^{-1} to 668.80 m^3 ha^{-1}. Despite the weak stastic significance, aparently diameter and volume recorded from Arufi Village provenance were better and least was from Binaturi provenance.

Genetic parameters of growth attributes of the provenances of *A. mangium* are given in Table 5. Genotypic coefficient of variation (GCV) and environmental coefficient of variation (ECV) of height were moderate at 15.29 percent and 11.64 percent, respectively. Diameter at breast height had low GCV (9.99%), but high for ECV (29.21%). The provenances had high GCV (38.57%) and ECV (39.04%) for volume.

Heritability of height was found to be high (63.30%). It was estimated to be low for DBH (25.98%) and moderate (49.39%) for volume. The study also showed that height (25.07%) and volume of the stand (55.83%) had high genetic gain, while genetic gain of DBH was found to be moderate (10.49%).

Table 5. Genetic parameters of height, DBH and volume in 14 years old provenances of *A. mangium*.

Characters	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genotypic	Environment		
Height (m)	15.29	11.64	63.30	25.07
DBH (cm)	9.99	29.21	25.98	10.49
Volume (m^3 ha^{-1})	38.57	39.04	49.39	55.83

4.1.2 Mean annual increment

Secondary data of nine years (from 2005 to 2013) of the trial plantation maintained by the AICRPAF were analyzed for MAI of DBH to evaluate the variation that exists between provenances (Table 6). The result showed that after 5 years of growth, MAI of DBH of all the provenances gradually reduced with age. The average MAI of DBH of all the provenances at 5th year was 2.83 cm year^{-1} and gradually reduced to 1.36 cm year^{-1} at 14th year. There was no significant different between the provenances in all the years. Highest MAI at 5th year was found for Kerala (3.11 cm) and Oriomo provenance (3.07 cm). Oriomo provenance continued as the best throughout the study period, while the local seed source were more subtle or even less in their performance compared to other provenances. At the 14th year, average MAI of Oriomo provenance for DBH was1.49 cm, closely followed by Upper Aramia and (1.46 cm) and Arufi Village (1.45 cm). Lowest MAI of DBH at the 14th year was from Binaturi provenance (1.24 cm), followed by Pascoe River and Lake Murray provenances, which had an average MAI of 1.28 cm for the DBH.

Table 6. Mean annual increment in DBH of the provenances of *A. mangium* grown in Thiruvazhamkunnu from 5 to 14 years of age (source: AICRPAF, 2005 to 2013).

Provenance	MAI of DBH (cm)									
	5th year	6th year	7th year	8th year	9th year	10th year	11th year	12th year	13th year	14th year
Tully-Mission Beach	2.80	2.53	2.19	1.99	1.99	1.89	1.61	1.44	1.34	1.30
Arufi Village	2.94	2.66	2.42	2.23	2.03	1.85	1.74	1.65	1.55	1.45
Claudie River	2.55	2.35	2.10	2.00	1.83	1.65	1.57	1.47	1.38	1.29
Oriomo WP	3.07	2.85	2.50	2.29	2.12	1.91	1.78	1.70	1.60	1.49
Kuranda	2.90	2.62	2.38	2.13	2.02	1.83	1.69	1.64	1.54	1.44
Pascoe River	2.83	2.52	2.22	2.07	1.88	1.70	1.59	1.47	1.37	1.28
Lake Murray	2.59	2.32	2.12	1.96	1.78	1.63	1.53	1.43	1.35	1.28
Balimo	2.69	2.45	2.18	2.04	1.87	1.71	1.65	1.54	1.45	1.35
Upper Aramia	2.85	2.66	2.35	2.18	2.03	1.85	1.76	1.69	1.57	1.46
Binaturi	2.76	2.50	2.16	2.00	1.80	1.68	1.52	1.42	1.33	1.24
Kerala	3.11	2.60	2.45	2.22	1.99	1.82	1.67	1.54	1.45	1.35
P	0.071^{ns}	0.169^{ns}	0.190^{ns}	0.477^{ns}	0.367^{ns}	0.526^{ns}	0.644^{ns}	0.255^{ns}	0.251^{ns}	0.364^{ns}

Superscript ‘ns’ indicates non-significant

4.1.3 Clear bole height

Clear bole height was evaluated for variation between provenances. The estimated clear bole height was also expressed as percentage of the total height of the tree and analyzed in the present study. Mean clear bole height and its percentage estimated for the 14 years old *A. mangium* of the different provenances are given in Table 7.

Table 7. Variation in clear bole height and clear bole percentage of the provenances.

Provenance	Clear bole height (m)	Clear bole (%)
Tully-Mission Beach	8.46	47.96
Arufi Village WP	9.82	43.53
Claudie River	8.79	44.58
Oriomo WP	7.15	38.70
Kuranda	9.24	43.42
Pascoe River	9.71	49.50
Lake Murray	8.36	45.81
Balimo	8.94	40.90
Upper Aramia	11.16	51.00
Binaturi	9.08	46.68
Kerala	10.22	50.74
Overall mean	9.18	45.71
P	0.608^{ns}	0.682^{ns}

Superscript ‘ns’ indicates non significant

The analysis of clear bole height and clear bole percentage showed no significant difference between the provenances. The overall mean estimated for clear bole height and clear bole percentage of the provenances was 9.13 m and 45.71

percent. Mean clear bole height of the provenances varied from 7.15 m to 11.16 m and variation in clear bole height percentage was from 38.70 percent to 51.00 percent. Highest clear bole height as well as highest clear bole percentage was recorded from Upper Aramia. Oriomo provenance had the lowest clear bole height and percentage.

Clear bole height of the provenances had moderate GCV (17.39%) and high ECV (29.28%). Heritability of the provenances for the trait was found to be low (26.08%), but genetic gain assuming at 5 percent level of selection intensity was high (18.30%).

4.1.4 Survival percentage

The survivals of trees in the trial plantation for each provenance were assessed and expressed as percentage at 14th year of growth (Table 8). The survival percentage did not differ significantly between the provenances. The overall mean of the provenances was 77.44 percent. Highest survival percentage of 96.30 percent was recorded from Kuranda and Upper Aramia provenance and the lowest (59.26%) was from Claudie River.

4.1.5 Tree form characters

To evaluate the variation in the tree form, each tree was assessed using visual scoring system. The scale of persistence of axis varied from 1 to 6. The score were arranged in such a way that high value would correspond to more desirable characteristics. Total number of trees that scored 4 to 6 was expressed as good axis percentage. The result is given in Table 9. While, for straight tree, branched thickness and mode of branching, the scale varied from 1 to 5. Similarly, the total numbers of tree that score 4 to 5 were expressed as percentage of trees having straight tree and light branched tree (Table 9).

Table 8 Mean survival percentage of the different provenances of 14 years old *A. mangium*

Provenance	Survival percentage
Tully-Mission Beach	88.89
Arufi Village WP	62.96
Claudie River	59.26
Oriomo WP	70.37
Kuranda	96.30
Pascoe River	77.78
Lake Murray	88.89
Balimo	66.67
Upper Aramia	96.30
Binaturi	81.48
Kerala	62.96
Overall mean	77.44
P	0.058^{ns}

Superscript ‘ns’ indicates non significant

The analysis using Friedman test showed no statistically significant difference between provenances in persistence of axis (χ^2 = 11.46; *P* = 0.323; *df* = 10), straightness (χ^2 = 12.85; *P* = 0.232; *df* = 10), branch thickness (χ^2 = 7.39; *P* = 0.688; *df* = 10) and mode of branching (χ^2 = 8.38; *P* = 0.591; *df* = 10). Similarly, univariate analysis showed no significant differences between provenances for good axis, straight tree, light branched tree and stem taper (Table9).

The overall mean of trees with good axis persistence was 51.68 percent. Mean of the provenances ranged from 24.80 percent to 65.83 percent. The overall mean for the percentage of straight trees and light branched trees were estimated to be 73.47 percent and 62.90 percent, respectively. The average number of trees having straight stem varied from 56.55 percent to 90.00 percent, while the percentage of light branched tree varied from 50.83 percent to 75.83 percent. The provenances were found to have good taper of stem. The overall mean of the provenances was 0.87. The mean of each provenance ranged from 0.84 to 0.91.

Table 9. Variation of the provenances of *A. mangium* in good axis, straight tree, light branched tree and taper of stem.

Provenance	Good axis (%)	Straight tree (%)	Light branched tree (%)	Taper
Tully-Mission Beach	56.20	72.35	57.32	0.85
Arufi Village WP	65.83	90.00	50.83	0.87
Claudie River	43.33	70.00	71.67	0.86
Oriomo WP	24.80	56.55	57.14	0.84
Kuranda	51.30	75.94	74.15	0.87
Pascoe River	63.59	74.40	60.71	0.91
Lake Murray	39.09	84.44	63.44	0.87
Balimo	61.11	70.83	59.72	0.89
Upper Aramia	51.48	61.11	65.19	0.90
Binaturi	47.50	65.00	75.83	0.87
Kerala	64.17	87.50	55.83	0.86
Overall mean	51.68	73.47	62.90	0.87
P	0.258^{ns}	0.166^{ns}	0.764^{ns}	0.124^{ns}

Superscript 'ns' indicates non significant.

Estimates for genetic parameters of good axis persistence, straight trees and light branched trees are given in Table 10. Environmental coefficient of variation was found to be higher than genotypic coefficient of variation in all the tree form characters. Good axis persistence had moderate GCV (12.77%), but low GCV (9.04

%) was observed in the proportion of tree having straight stem, light branched tree (8.72%) and taper of tree stem (1.55%).

Table 10. Genetic parameters of tree form characters and branching habit of the provenances.

Characters	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genotypic	Environment		
Good axis	12.77	20.68	27.59	13.82
Straight tree	9.04	11.29	39.09	11.64
Light branched tree	8.72	9.42	46.11	12.18
Taper	1.55	1.72	44.84	2.30

Heritability of the characters was low to moderate. The percentage of trees having good axis (27.59%) had low heritability, while straight tree (39.09%) and light branched trees (46.11%) had moderate heritability. Genetic gain was found to be moderate for percentages of good axis persistence (13.82%), straight trees (11.64%) and light branched trees (12.18%), but low for stem taper (2.30%).

4.1.6 Stability analysis for growth

The different provenances obtained from Queensland and Papua New Guinea were analyzed for stability in growth of DBH. In order to estimate the stability, interaction between the genotype and environment were analyzed for the ten years period of growth using AMMI model. The analysis of variance is summarized in Table 11.

The result showed no significant interaction between genotype × environment in DBH (P = 1.000, df = 90). However, the interaction of the genotype (P = 1.824, df = 10) and environment (P = 90.66, df = 9) on DBH were significant. For DBH, the percentage contribution of Interaction Principal Components Analysis (IPCA) showed that majority (81.4%) of the variation were explainable by IPCA1, while 8.92 percent of the total interaction sum of squares were accounted by IPCA2. However, their contributions were statistically not significant.

Table 11. Analysis of variance of MAI of DBH of ten years period (AICRPAF, 2005 to 2014) for the provenances by AMMI model.

Response	*df*	MS	*F* Value	Contribution of IPCA components (%)	Probability
Genotype	10	0.37	7.76	-	1.824***
Environment	9	7.94	90.66	-	3.109***
Genotype × environment	90	0.008	0.16	-	1.000^{ns}
IPCA1	18	0.032	0.66	81.4	0.847^{ns}
IPCA2	16	0.003	0.08	8.9	1.000^{ns}
G×E Residuals	200	0.048	-	-	-

df = degrees of freedom; MS = Mean square; IPCA = interaction principal component analysis.
*** significant at 0.1 percent and superscript 'ns' indicates non significant.

Scores of IPCA1 and IPCA2 of each provenance for DBH are given in Table 12. The IPCA1 showed positive interaction with main effect of Tully-Mission Beach (0.08), Arufi Village (0.03), Oriomo (0.19), Pascoe River (0.09), Binaturi (0.06) and Kerala seed source (0.42), but negatively interacted with rest of the provenances. Negative interaction of IPCA1 with the provenances ranged from -0.01 to -0.33. Highest positive interaction was associated with the Kerala seed source and lowest negative interaction was with the Kuranda provenance.

IPCA2 had positive interaction with Arufi Village (0.01), Balimo (0.03), Claudie River (0.04), Kerala seed source (0.21), Lake Murray (0.18) and Pascoe (0.02), but negatively interacted with Upper Aramia (-0.11), Binaturi (-0.06), Kuranda (-0.01) and Oriomo (-0.20) provenances.

Table 12. Scores of IPCA1 and IPCA2 of each provenance for DBH.

Provenance	IPCA1	IPCA2
Tully-Mission Beach	0.08	-0.09
Arufi Village	0.03	0.01
Claudie River	-0.33	0.04
Oriomo	0.19	-0.20
Kuranda	-0.01	0.01
Pascoe River	0.09	0.02
Lake Murray	-0.19	0.18
Balimo	-0.23	0.03
Upper Aramia	-0.10	-0.11
Binaturi	0.06	-0.06
Kerala	0.42	0.21

To illustrate the effect of each genotype and environment on DBH, the AMMI1 (IPCA vs. means) and AMMI2 (IPCA2 vs. IPCA1) biplots are shown in Figures 2 and 3, respectively. In the Figure 2, the X-coordinate indicates the main effects (mean of DBH of the provenances) and the Y-coordinate indicates the effects of the IPCA1. Values closer to the origin of the axis had smaller contribution to the interaction than those that are further away. In the present study, Arufi Village and

Kuranda provenances were the most stable provenance, followed by Upper Aramia and Pascoe River provenances. Kerala seed source and Claudie River provenances were the least stable followed by Balimo and Murray, while Tully-Mission Beach and Binaturi provenances were intermediate. Interaction of IPCA1 with DBH of the provenances also showed that there were no much differences in the main effect between the provenances.

The interaction of DBH with IPCA1 and IPCA2 revealed that Kuranda and Arufi Village had the highest stability compared to other provenances (Figure 3). Kerala seed source and Claudie River was the most sensitive to IPCA1 and 2. The interaction with Kerala seed source was positive, while the interaction with Claudie River was negative. Provenances of Pascoe River, Binaturi, Tully-Mission Beach and Upper Aramia were more stable than Lake Murray, Balimo and Oriomo provenances. The environment that prevailed during the year 2005 had the highest interaction with the provenances in their growth attributes, while the interaction was found to be the lowest during 2009.

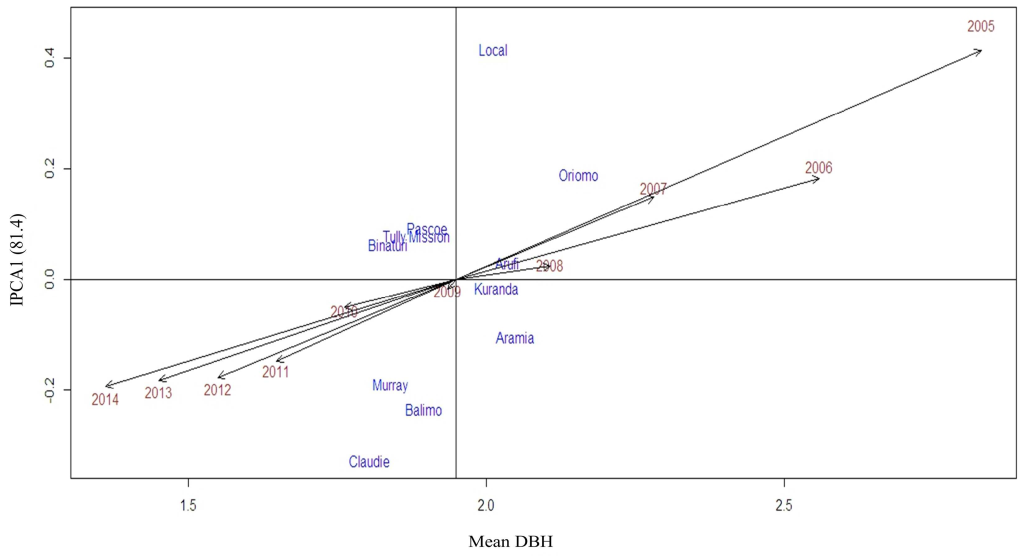

Figure 2. Biplot of IPCA1 vs. mean DBH of the provenances of *A. mangium*.

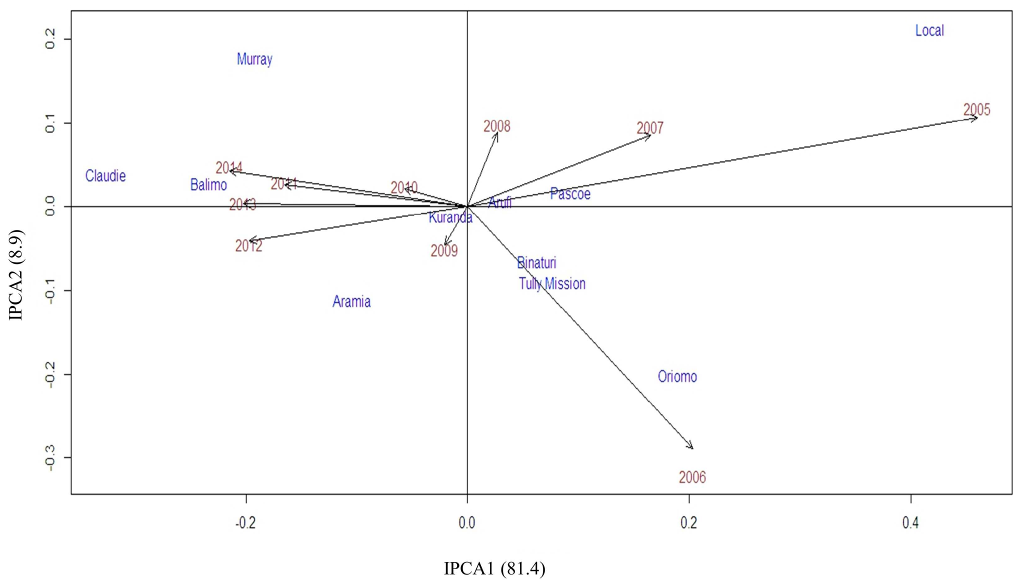

Figure 3. Biplot of IPCA analysis for DBH in *A. mangium*.

4.2 PART II

4.2.1 Morphometric traits of seeds

Morphometric traits of seeds *viz.* seed weight, length, width and thickness, were studied to investigate the variations associated with the different provenances and the result of analysis and mean values are summarized in the Table 13. The average seed weight, length, width and thickness of the provenances were found to be 282.28 mg, 4.08 mm, 2.52 mm and 1.45 mm, respectively. The analysis showed significant difference between the provenances for seed weight, length, width and thickness.

Seed weight of Arufi Village provenance (331.98 mg) was found to be the highest, followed by Claudie River (298.15 mg) and Binaturi (297.48 mg) provenances. Post-hoc comparison revealed that the mean seed weight of Arufi Village provenance was significantly higher than all other provenances, while Tully-Mission Beach (181.85 mg), Balimo (284.05 mg), Pascoe River (286.10 mg) and Kuranda (293.02 mg) were on par with Claudie River and Binaturi provenances. Lowest seed weight (215.68 mg) was from Kerala seed source, followed by Lake Murray (264.32 mg) and Upper Aramia (271.32 mg) provenances.

The provenance of Pascoe River had the highest seed length (4.22 mm). The seed length was found to be significantly higher than most of the provenances, except the seed length of Tully-Mission Beach provenance (4.20 mm). Arufi Village (4.09 mm) and Balimo (4.13 mm) provenances were on par with Tully-Mission Beach provenance. Kerala seed source had the lowest seed length (3.75 mm) and differed significantly from other provenances. Seed length of the provenances of Claudie River, Oriomo, Kurada, Lake Murray, Upper Aramia and Binaturi did not differ significantly from each other. The seed length of the provenances varied from 4.04 mm to 4.12 mm.

Seed width was found to be the highest in Arufi Village provenance (2.76 mm) and differed significantly from all other provenances. Kerala seed source (2.32 mm) had the lowest seed width, followed by Oriomo provenance (2.49 mm). Seed width of Kerala seed source differed significantly from all other provenances. Oriomo provenance differed significantly in seed width with Arufi Village, Claudie River (2.57 mm) and Kerala seed source. The rest of the provenances had more or less the same seed width.

Seed thickness of Arufi Village provenance (1.57 mm) was also found to be significantly higher than the other provenances, it was followed by Kuranda provenance (1.52 mm). Claudier River (1.50 mm) was on par with Kuranda provenance. Thinnest seed was associated with Kerala seed source (1.39 mm), Balimo (1.39 mm), Tully-Mission Beach (1.39 mm) and Upper Aramia (1.40 mm). They did not differ significantly from each other. Oriomo and Binaturi provenances were on par with the latter provenances and their mean seed thickness was 1.42 mm.

Estimates of variability, heritability and genetic gain for the morphometric traits are given in Table 14. The result showed that GCV and ECV were low (<10%) for all the characters studied. Seed weight had the highest GCV (9.85%) followed by seed length (3.99%), thickness (3.94%) and width (2.99%). Environmental coefficient of variance was also found to be the highest in seed weight (1.74%) and the least was in seed length (0.77%). Seed width and seed thickness had similar ECV (0.82%).

Heritability was high for all the morphometric traits of seeds. Seed weight (96.98%) and width (96%) had the highest heritability among the traits. Least heritable trait among the morphometric traits of seeds was thickness (92.77%).

Table 13. Variation in the morphometric traits of seeds of the provenances.

Provenance	Seed weight (mg)	Seed length (mm)	Seed width (mm)	Seed thickness (mm)
Tully-Mission Beach	282.85^{bcd}	4.20^{ab}	2.46^{cd}	1.39^{f}
Arufi Village WP	331.98^{a}	4.09^{bc}	2.76^{a}	1.57^{a}
Claudie River	298.15^{b}	4.12^{cd}	2.57^{bc}	1.50^{bc}
Oriomo WP	280.15^{cd}	4.06^{d}	2.49^{d}	1.42^{ef}
Kuranda	293.02^{bc}	4.07^{d}	2.50^{bcd}	1.52^{b}
Pascoe River	286.10^{bcd}	4.22^{a}	2.56^{bc}	1.46^{cd}
Lake Murray	264.32^{e}	4.04^{d}	2.50^{cd}	1.45^{de}
Balimo	284.05^{bcd}	4.13^{bc}	2.49^{cd}	1.39^{f}
Upper Aramia	271.32^{de}	4.07^{d}	2.51^{bcd}	1.40^{f}
Binaturi	297.48^{b}	4.07^{d}	2.55^{bcd}	1.42^{ef}
Kerala	215.68^{f}	3.75^{e}	2.32^{e}	1.39^{f}
Overall mean	282.28	4.08	2.52	1.45
P	0.000*	0.000*	0.000*	0.000*

Mean values with similar superscript along the column do not differ significantly.
* * Significant at 1 percent level and superscript 'ns' indicates non significant.

Table 14. Genetic parameters for morphometric traits of the provenances of *A. mangium.*

Characters	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genotypic	Environment		
Seed weight (mg)	9.85	1.74	96.98	56.4
Seed length (mm)	2.99	0.77	93.80	24
Seed width (mm)	3.99	0.82	96.00	20
Seed thickness (mm)	3.94	0.82	92.77	23

Morphometric traits of seeds in the study had moderate (10% to 20%) to high (>20%) genetic gain. Genetic gain of seed weight (56%), seed length (24%) and thickness (23%) was high, while seed width (20%) was moderate. Therefore, highest genetic gain was in seed weight followed by seed length, thickness and width.

4.2.2 Viability

Seeds of the provenances were tested for viability using triphenyl tetrazolium chloride (0.3%) and the staining pattern was observed under the magnifying glass. Staining of seeds in the present study followed only three patterns under the two categories *viz.* viable and non-viable seeds (Table 2). Viable seeds of the provenances were found to follow two patterns. Majority of the viable seeds had staining pattern that fall under the description of embryo and cotyledons completely stained, while the staining pattern of few seeds were under the description of embryo completely stained and cotyledons stained except for occasional small unstained patches here and there. The non-viable seeds were of those that had an embryo unstained and cotyledons completely stained near embryo. The number of seeds that found viable were recorded and expressed as percentage (Table 15).

Since, the viability percentages were not normally distributed, arcsine transformation method was done prior to statistical analysis. Univariate analysis was then followed. The analysis of variance showed no significant difference between the provenances. The average viability of the entire provenances was 97.66 percent. The viability ranged from 93.3 percent to 100 percent. Tully-Mission Beach, Oriomo, Kuranda and Kerala seed source had 100 percent viable seeds. Seed viability of Balimo provenance was the least (93.3%).

Table 15. Seed viability percentage of the provenances

Provenance	Viability (%)
Tully-Mission Beach	100
Arufi Village WP	96.67
Claudie River	96.67
Oriomo WP	100
Kuranda	100
Pascoe River	97
Lake Murray	97
Balimo	93.3
Upper Aramia	97
Binaturi	96.67
Kerala	100
Overall mean	97.66
P	0.589^{ns}

Superscript ‘ns’ indicates non significant

4.2.3 Water imbibition of seeds

In order to test the nature of seed dormancy of *A. mangium*, the increase in seed mass after 24 hours as a result of imbibition of water by the seeds, which is expressed as percentage, were compared between the seeds that were used as control and the seeds of the provenances treated with hot water. Univariate analysis was performed to compare the effect. The results are presented in Table 16.

Table 16. Increased in seed mass due to imbibition of water of treated and control seeds after 24 hours of soaking in water prior to germination test.

Sl. No.	Treatment	Increase in seed mass (%)
1	Tully-Mission Beach	7.66[bcde]
2	Arufi Village WP	5.99[bcde]
3	Claudie River	14.34[ab]
4	Oriomo WP	1.810[e]
5	Kuranda	4.04[cde]
6	Pascoe River	12.12[abc]
7	Lake Murray	18.45[a]
8	Balimo	11.42[abcd]
9	Upper Aramia	7.40[bcde]
10	Binaturi	5.36[cde]
11	Kerala	4.34[cde]
12	Control	3.02[de]
P		0.001*

Sl. no. 1 to 11 – treated with hot water; control – seed without hot water treatment but soaked in cold water for 24 hours.
Mean values with similar superscript along the column do not differ significantly.
* Significant at 5 percent level.

The analysis showed significant differences between the treated and control seeds as well as among the treated groups. The average increase in seed mass of hot water treated seed ranged from 1.81 percent to 18.45 percent, while the mean of the control was 3.02 percent. Highest increase in seed mass was from the treated seeds of Lake Murray provenance (18.45%). The increase in seed mass of the provenances of Claudie River (14.34%), Pascoe River (12.12%) and Balimo (11.42%) were on par with the Lake Murray provenance. Increase in seed mass was found to be the lowest in Oriomo provenance (14.34%). The other provenances that were on par with the

Oriomo provenance were control (3.02%), Kuranda (4.04%), Kerala seed source (4.34%), Binaturi (5.36%), Arufi Village (5.99%), Upper Aramia (7.40%) and Tully-Mission Beach (7.66%).

4.2.4 Germination

To evaluate the variation associated with the provenances in germination related parameters, germination test was conducted in the laboratory after the treatment of seeds with hot water and soaking them for 24 hours in cold water. The control seeds were also tested for germination in parallel with the germination test of the various provenances, but no seeds were found to germinate during the study period. The different parameters investigated in the study and results of the analysis are presented in Table 17 and the overall mean of the provenances are given in Table 18.

The provenances differed significantly for germination percentage, germination energy, germination value and germination period. The overall mean estimated for germination percentage was 82.18 percent. Highest germination percentage was found in Lake Murray provenance (94%). The germination percentage of Binaturi (91%), Arufi Village (85%), Claudie River (86%), Balimo (80%) and Upper Aramia (80%) were on par with Lake Murray provenance. Lowest germination percentage was from Kuranda (72%). The Kuranda provenance differed significantly from Lake Murray, Binaturi and Tully-Mission Beach. Germination percentage was found to be significantly correlated (5% level) with increase in seed mass due to imbibitions of water. The correlation coefficient between the traits was 0.286.

Germination value of the provenances had an overall mean of 26.46 percent. Lake Murray provenance also had the highest germination value (46.52) which was significantly different from the other provenances. The remaining ten provenances did not differ significantly from each other. In case of germination energy, which had an overall mean of 49, the provenances of Claudie River, Tully-Mission Beach, Arufi Village, Balimo, Binaturi and Kerala seed source were found to be the highest. They did not differ significantly from each other and the germination energy among them ranged from 48 percent to 72 percent. The lowest germination energy was recorded from Pascoe River (32), followed by Upper Aramia (35%) and Kuranda (38%). The three provenances showed significant difference with the Claudie River and Tully-Mission Beach provenances.

Germination period, which is the number of days for germination to reach 80 percent or more from the total number of germinated seeds, had an overall mean of 9.96 days. It was found to be the longest in the seeds obtained from Arufi Village provenance (12 days). Lake Murray provenance had the shortest days (7 days) and differed significantly from Arufi Village, Upper Aramia (12 days), Tully-Mission Beach (12 days) and Binaturi (12 days).

Germination capacity was found to deviate from normal distribution. Therefore, prior to the statistical analysis, arcsine transformation was done. Analysis of germination capacity showed no significant differences between the provenances as well as with the control. The overall mean of germination capacity for the provenances was 95.64 percent. Germination capacity of the provenances ranged from 90 percent to 99 percent. The control had an average mean germination capacity of 92.75 percent. It did not differ significantly from any of the provenances.

Table 17. Variation in germination related parameters of seed of the provenances and control.

Sl. no.	Provenance	G (%)	GV	GE (%)	GP (day)	GC (%)
1	Tully-Mission Beach	88.00^{abc}	25.80^{b}	68.00^{ab}	11.75^{abc}	97.00
2	Arufi Village WP	85.00^{abcd}	21.43^{b}	54.00^{abc}	12.50^{a}	94.00
3	Claudie River	86.00^{abcd}	30.62^{b}	72.00^{a}	9.00^{bcde}	93.00
4	Oriomo WP	76.00^{bcd}	19.93^{b}	43.00^{bc}	10.00^{bcde}	98.00
5	Kuranda	72.00^{d}	21.61^{b}	38.00^{c}	8.75^{cde}	99.00
6	Pascoe River	75.00^{cd}	26.52^{b}	32.00^{c}	8.50^{de}	97.00
7	Lake Murray	94.00^{a}	46.52^{a}	44.00^{bc}	7.25^{e}	97.00
8	Balimo	80.00^{abcd}	24.64^{b}	48.00^{abc}	9.50^{bcde}	90.00
9	Upper Aramia	80.00^{abcd}	21.14^{b}	35.00^{c}	12.00^{ab}	95.00
10	Binaturi	91.00^{ab}	25.56^{b}	57.00^{abc}	11.50^{abcd}	96.00
11	Kerala	77.00^{bcd}	27.36^{b}	48.00^{abc}	8.75^{cde}	96.00
12	Control	0^{e}	0^{c}	0^{d}	0^{f}	92.75
P		0.041*	0.000*	0.028*	0.007*	0.212^{ns}

Sl. no. 1 to 11 – treated with hot water; Sl. no. 12 – seed without hot water treatment but soaked in cold water for 24 hours. G - germination percentage; GV – germination value; GE – germination energy; GP – germination period.
Mean values with similar superscript along the column do not differ significantly.
* indicates significant at 5 percent level and superscript ‘ns’ indicates non-significant.

Genetic parameters like variability, heritability and genetic gain was also estimated for the germination related parameters of the provenances. The result is presented in Table 18. Genetic coefficient of variation for all the germination related parameters was higher than the environmental coefficient of variation. Genetic coefficient of variation was low for germination percentage (6.45%), moderate for germination energy (20.15%) and germination period (14.29%), but high for germination value (25.06%). Environmental coefficient of variation was low in germination percentage (5.74%) and germination period (9.78%), but it was found to be moderate for germination energy (16.75%) and germination value (12.26%). Heritability was found to be moderate for germination percentage (55.84%) and germination energy (59.13%), but it was high for germination period (68.09 %) and germination value (80.67%). The highest genetic gain was in germination energy (15.64%), while the least was in germination period (2.42%). Genetic gain of germination percentage (8.16%) and germination period was low. Moderate genetic gain was associated with germination energy and germination value (12.27%).

Table 18. Genetic parameters of germination related parameters of the provenances.

Characters	Overall mean	Coefficient of variation (%)		Heritability (%)	Genetic gain
		genotypic	Environment		
Germination (%)	82.18	6.45	5.74	55.84	8.16
Germination value	26.46	25.06	12.26	80.67	12.27
Germination energy	49.00	20.15	16.75	59.13	15.64
Germination period	9.96	14.29	9.78	68.09	2.42

4.2.5 Seedling growth

For studying the variation in the seedling performances of the provenances in the nursery, seedlings height, collar girth and RGR were recorded at an interval of 30 days. In addition to the variation in their performances, genetic parameters associated with the traits were also determined. The results of the observations are explained below.

4.2.5.1 *Height of seedlings*

The performance of seedlings of the provenances in height was recorded from second to fifth month of growth (Figure 4). The variation in the mean height at different stages of growth and their analysis are given in Table 19.

The analysis of variance for height showed no significant difference between the provenances at two months of growth. The overall mean height of the seedlings was 10.87 cm. The height of the provenances ranged from 9.34 cm to 11.84 cm. Three month old seedlings of the provenances had an overall mean of 14.56 cm. Significant difference between provenances in height was observed in three month old seedlings. Three months old seedlings of Lake Murray provenance (16.78 cm) were found to be significantly higher than Upper Aramia (13.34 cm), Balimo (13.32 cm) and Kerala (12.36 cm), while the rest of the provenances were on par with Lake Murray provenance. Provenances of Tully-Mission Beach (14.51 cm), Claudie River (14.70 cm), Oriomo (14.71), Kuranda (14.82 cm) and Arufi Village (14.92 cm) were also found to be on par with Upper Aramia, Balimo and Kerala.

Four month old seedlings of the provenances had an average height of 18.52 cm. Height was found to be significantly different between provenances. Lake Murray provenance (22.44 cm) had the highest seedlings for the four month old seedlings and the Kerala seed source (15.34 cm) was among the provenances having the shortest height of seedlings. The two provenances differ significantly from each other, but all the other provenances had more or less the same height at the stage. The provenances of Binaturi (19.84 cm), Kuranda (19.82 cm), Pascoe River (19.48 cm) and Arufi Village (19.02 cm) were on par with Lake Murray, while the provenances of Upper Aramia (16.28 cm), Balimo (16.64 cm), Tully-Mission Beach (18.21 cm), Oriomo (18.21 cm) and Claudie River (18.42 cm) did not differ significantly from Kerala seed source.

Table 19. Variation in seedling height of the different provenances during the five month periods of growth.

Provenance	Height (cm)			
	Second month	Third month	Fourth month	Fifth month
Tully-Mission Beach	10.78	14.51^{abc}	18.21^{bc}	20.86^{bcd}
Arufi Village WP	10.99	14.92^{abc}	19.02^{ab}	21.78^{bc}
Claudie River	10.91	14.70^{abc}	18.42^{bc}	20.92^{bcd}
Oriomo WP	11.19	14.71^{abc}	18.21^{bc}	20.50^{bcd}
Kuranda	10.62	14.82^{abc}	19.82^{ab}	23.76^{ab}
Pascoe River	11.50	15.18^{ab}	19.48^{ab}	22.71^{abc}
Lake Murray	12.28	16.78^{a}	22.44^{a}	25.64^{a}
Balimo	9.94	13.32^{bc}	16.64^{bc}	19.49^{cd}
Upper Aramia	10.21	13.34^{bc}	16.28^{bc}	19.10^{cd}
Binaturi	11.84	15.52^{ab}	19.84^{ab}	23.00^{abc}
Kerala	9.34	12.36^{c}	15.34^{c}	17.65^{c}
Overall mean	10.87	14.56	18.52	21.40
P	0.185^{ns}	0.041*	0.005*	0.003*

Mean values with similar superscript along the column do not differ significantly.
* significant at 5 percent level and superscript ‘ns’ indicates non significant.

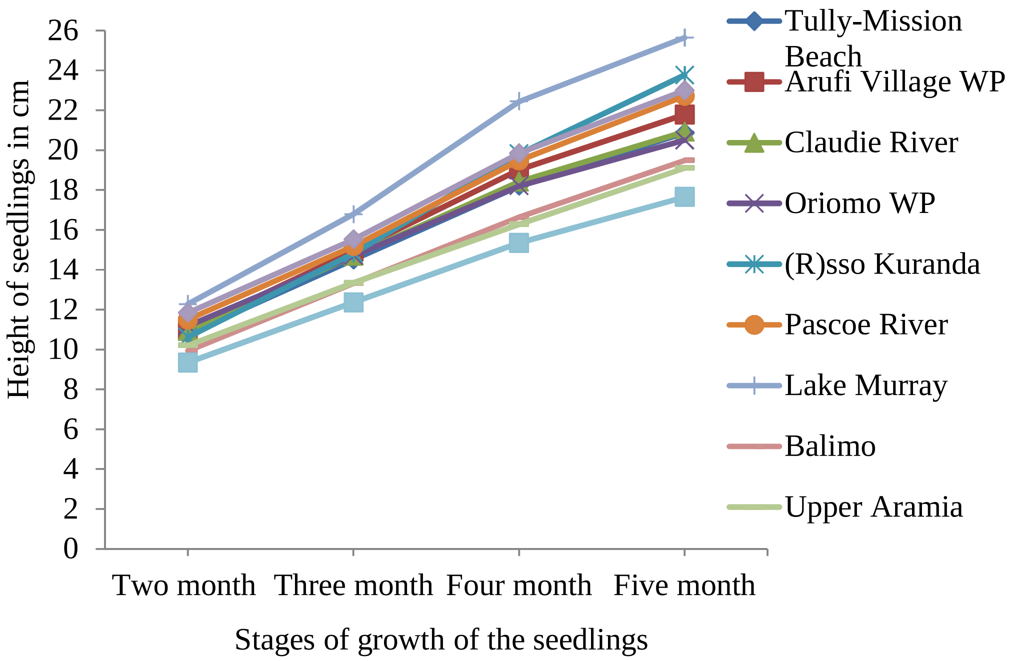

Figure 4. Growth of height for seedlings of the provenances during the five month periods.

Five month old seedlings continued to exhibit significant differences between provenances. The overall mean of five month old seedling height was 21.40 cm. At the stage, seedling height of Lake Murray (25.64 cm), Kuranda (23.76 cm), Binaturi (23 cm) and Pascoe River (22.71 cm) continued to perform the best. Provenances of Kuranda, Binaturi and Pascoe River did not differ significantly from all other provenances. The mean height of seedling of Kerala seed source (17.65 cm) was among the least, followed by Upper Aramia (19.10 cm) and Balimo (19.49 cm). However, Kerala seed source did not differ significantly from the rest, except Lake Murray and Kuranda.

Genetic parameters of seedlings height are given in Table 20. Low genetic and environmental coefficient of variance was found to be associated with seedling height. Comparatively, GCV of height was higher than ECV in almost all the stages, except for two month old seedlings (Figure 5). Five month old seedling has the highest GCV (9.08%) and lowest (4.51%) was for two month old seedlings. For ECV, highest (6.32%) was from two month old seedlings and lowest (5.46%) was recorded from three month old seedlings.

In the present study, the result of the analysis of variance of the provenances of five month old seedlings was used for estimating heritability. Heritability of height of seedlings at the stage was found to be high (72.23%). On the other hand, five month old seedlings had moderate genetic gain (15.90%).

Table 20. Genetic parameters of height of seedlings of the provenances of *A. mangium*.

Age of seedlings	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genotypic	Environment		
Two month	4.51	6.32		
Three month	6.13	5.46		
Four month	8.88	5.85		
Five month	9.08	5.63	72.23	15.90

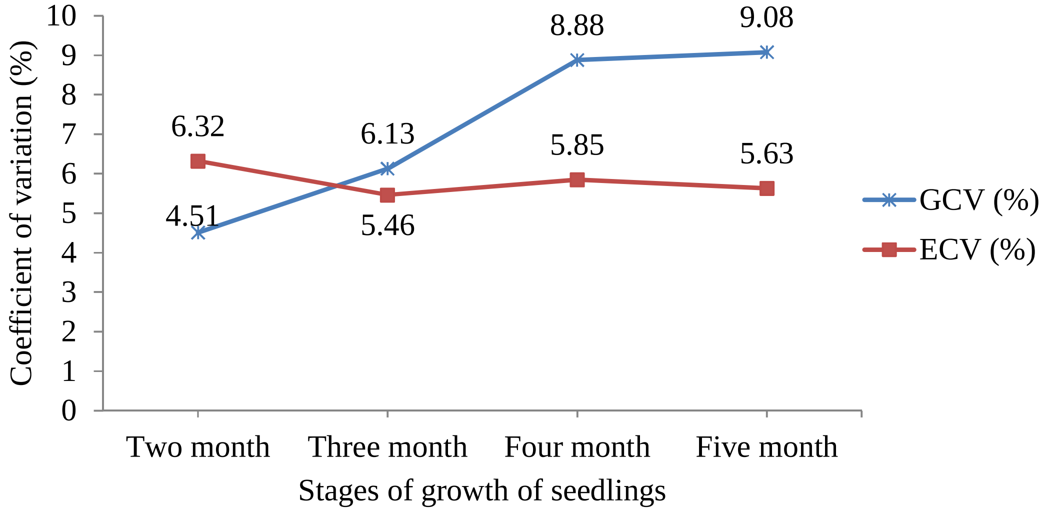

Figure 5. Genotypic coefficient of variation and environmental coefficient of variation in seedling height at different stages of growth.

4.2.5.2 *Collar girth*

Variation in mean collar girths of the provenances recorded at two, three, four and five month old seedlings are given in Table 21. The analysis of variance showed no significant difference between the provenances at any stages.

Overall mean collar girth of seedling of the provenances at two month was 1.62 mm. The average girth of seedlings of the provenances ranged from 1.42 mm to 1.76 mm. Lake Murray provenance had the highest mean of collar girth, closely followed by Binaturi provenance (1.75 mm). Least collar girth was from Kerala seed source. Seedlings of the provenances at three month had an average collar girth of 2.29. The variation in girth at the stage varied from 2.06 mm to 2.50 mm. The mean collar girth of Lake Murray was the highest and the lowest was from Kerala seed source. Four months old seedlings of the provenances had an overall mean collar girth of 2.84 mm. Collar girth of 2.51 mm of Kerala seed source was found to be the minimum and 3.08 mm of Lake Murray provenance was the maximum for the seedlings of the provenances at the stage. The overall mean of collar girth increased to 3.31 mm for five month old seedlings of the provenances. The collar girth varied from 3.06 mm to 3.56 mm. Highest mean of collar girth was found in Kuranda, closely followed by Lake Murray provenance (3.54 mm), while the lowest mean was from Kerala seed source.

Genetic parameters estimated for collar girth at different stages of seedlings of the provenances are presented in Table 22. Collar girth of seedlings of the various provenances had low GCV and ECV at all the stages. Environmental coefficient of variance was higher than GCV (Figure 6) and GCV of height was always higher than GCV of DBH (Figure 7). In general, GCV and heritability of collar girth tend to increase with age. Highest GCV of 4.47 percent was in four months old seedlings and lowest (3.46%) was in three month old seedlings. Environmental coefficient of

Table 21. Variation in collar girth of seedlings of the provenances of *A. mangium* during the five month periods of growth.

Provenance	Collar girth (mm)			
	Two month	Three month	Four month	Five month
Tully-Mission Beach	1.64	2.21	2.66	3.10
Arufi Village WP	1.68	2.30	2.91	3.42
Claudie River	1.67	2.34	2.77	3.25
Oriomo WP	1.62	2.38	2.96	3.25
Kuranda	1.65	2.35	2.97	3.56
Pascoe River	1.64	2.34	2.99	3.51
Lake Murray	1.76	2.50	3.08	3.54
Balimo	1.49	2.18	2.73	3.17
Upper Aramia	1.53	2.10	2.67	3.17
Binaturi	1.75	2.40	2.93	3.39
Kerala	1.42	2.06	2.51	3.06
Overall mean	1.62	2.29	2.84	3.31
P	0.200^{ns}	0.177^{ns}	0.058^{ns}	0.103^{ns}

Superscript 'ns' indicates non significant

Table 22. Genetic parameters of collar girth of seedling of the provenances of *A. mangium.*

Age of seedlings	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genotypic	Environment		
Two month	3.54	5.32		
Three month	3.46	4.74		
Four month	4.47	4.28		
Five month	3.68	4.10	44.61	5.06

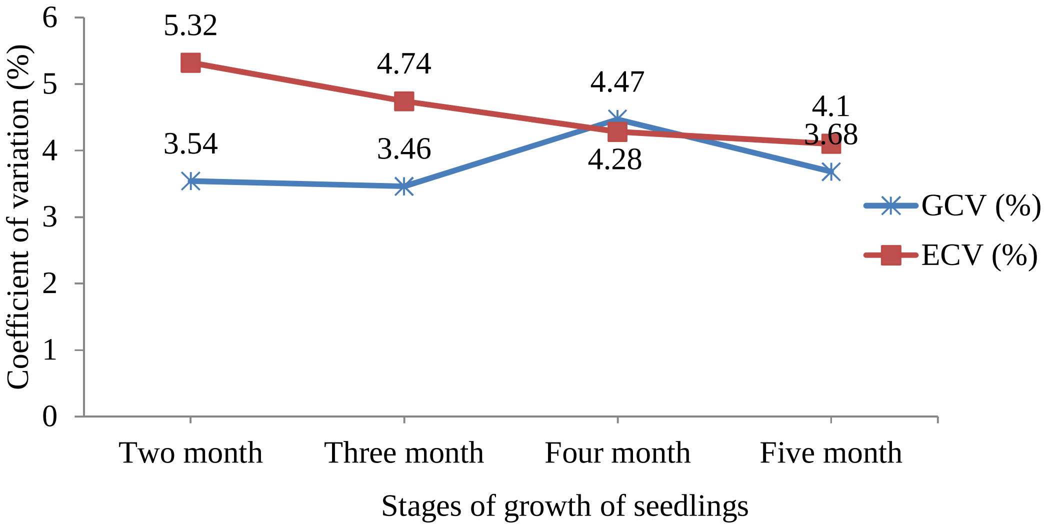

Figure 6. Genotypic coefficient of variation and environmental coefficient of variation in collar girth of seedling height at different stages of growth.

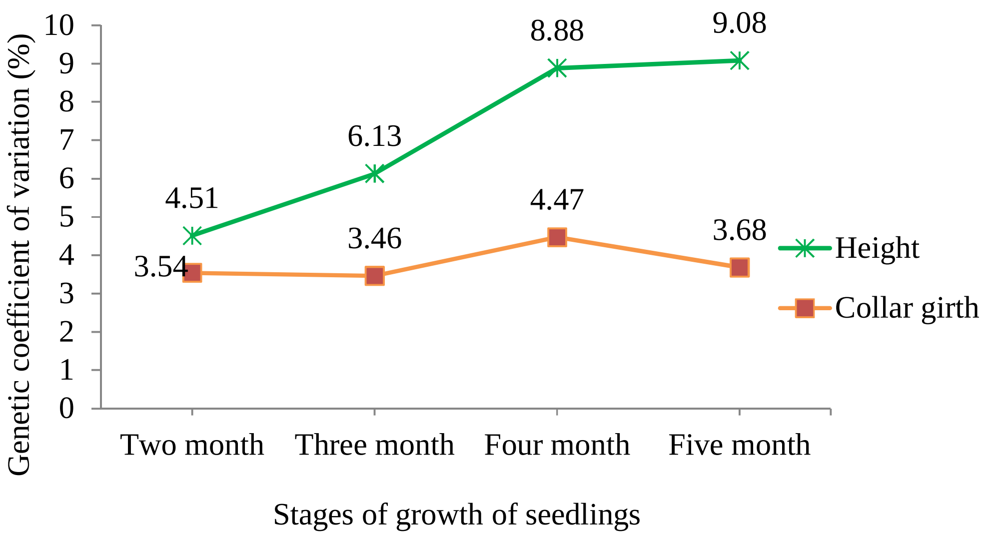

Figure 7. Comparison between the GCV of height and collar girth of seedling of the provenances at different stages of growth.

variation of collar girth was found to be the highest (5.32%) in two month old seedling and lowest (4.10%) in five month old seedlings.

Heritability of collar girth was estimated at five month old seedlings of the provenances. It was found to be moderate (44.61%). Genetic gain was low for collar girth (5.06%) of the seedlings.

4.2.5.3 ***Relative growth rate***

Variations in the growth rate of seedlings of the provenances were determined by destructive sampling. Seedlings were randomly selected from each replication and their fresh- and dry-weight were recorded for five months. The results of analysis are presented in Table 23.

No significant differences between the provenances for RGR were observed in the present study. One month old seedlings had the highest RGR. The overall mean of RGR recorded at the period was 0.159 g g^{-1} $month^{-1}$. Mean of the provenances varied from 0.136 g g^{-1} $month^{-1}$ to 0.172 g g^{-1} $month^{-1}$. Kuranda provenance had the highest RGR at the stage. The provenance was closely followed by Claudie River provenance (0.171 g g^{-1} $month^{-1}$). One month old seedlings of Upper Aramia had the lowest RGR.

Relative growth rate of two month old seedlings of the provenances had an overall mean of 0.040 g g^{-1} $month^{-1}$. The performance of the provenances varied from 0.027 g g^{-1} $month^{-1}$ to 0.052 g g^{-1} $month^{-1}$. Three months old seedlings of Upper Aramia had the highest RGR and the lowest was from Pascoe River provenances.

The overall mean further reduces to 0.030 g g^{-1} $month^{-1}$ for three month old seedlings. At the stage, RGR range from 0.009 g g^{-1} $month^{-1}$ to 0.048 g g^{-1} $month^{-1}$. The highest RGR was recorded from Claudie River provenance and the lowest was from Lake Murray provenance. At four month, overall mean of RGR increased to 0.034 g g^{-1} $month^{-1}$. Lowest RGR during the month was recorded from the provenance of Oriomo (0.017 g g^{-1} $month^{-1}$) and the highest was from Kuranda (0.058 g g^{-1} $month^{-1}$). The RGR of the five month old seedlings reduces to 0.024 g g^{-1} $month^{-1}$. Relative growth rate at the period ranged from 0.014 g g^{-1} $month^{-1}$ to 0.038 g g^{-1} $month^{-1}$. The lowest RGR was from Kerala seed source and the highest was from Upper Aramia provenance.

Table 23. Variation in relative growth rate of seedlings of the provenances of *A. mangium*.

Provenance	Relative Growth Rate (g g^{-1} $month^{-1}$)				
	One month	Two month	Three month	Four month	Five month
Tully-Mission Beach	0.162	0.043	0.022	0.024	0.020
Arufi Village WP	0.165	0.042	0.031	0.045	0.020
Claudie River	0.171	0.032	0.048	0.027	0.026
Oriomo WP	0.154	0.035	0.032	0.017	0.030
Kuranda	0.172	0.046	0.034	0.058	0.022
Pascoe River	0.159	0.027	0.040	0.047	0.025
Lake Murray	0.164	0.045	0.009	0.053	0.018
Balimo	0.156	0.031	0.031	0.028	0.021
Upper Aramia	0.136	0.052	0.033	0.038	0.038
Binaturi	0.158	0.048	0.025	0.023	0.014
Kerala	0.148	0.036	0.027	0.020	0.028
Overall mean	0.159	0.040	0.030	0.034	0.024
P	0.205^{ns}	0.928^{ns}	0.231^{ns}	0.398^{ns}	0.880^{ns}

Superscript ‘ns’ indicate non significant.

4.2.6 Correlation between the morphometric traits, germination parameters and seedlings growth

The correlation between different morphometric traits, germination parameters and seedling growth were studied. The results are given in Table 24. Germination related parameters did not show any significant correlation with the seed morphometric traits and seedling heights at different growth periods, while the correlation between seed morphometric traits and seedling heights at the same stage was significant.

In the present study, correlation between germination percentage with seed weight and width was 0.131 and 0.123, respectively, while the correlation with seed length (-0.086) and thickness (-0.040) was negative. The correlation between germination percentage and height of the seedlings at different stages ranged from 0.098 to 0.120.

Germination value of seeds had weak and negative correlation with seed morphometric traits, but it had weak and positive correlation with height of the seedlings at different stages. The correlation between germination value and seed morphometric traits ranged from -0.042 to -0.210 and correlation with seedling heights ranged from 0.137 to 0.197.

The correlation between germination energy with seed weight and width of morphometric traits of seeds was 0.163 and 0.144, respectively. Seed length (-0.009) and thickness (-0.019) of the morphometric traits of seeds had very weak and negative correlation with germination energy. The correlation of germination energy with two, three, four and five month old seedling height was 0.124, 0.024, -0.034 and -0.039, respectively.

Table 24. Correlation between the morphometric traits of seeds, germination related parameters and seedling height of the provenances.

	Seed weight	Seed length	Seed width	Seed thickness	Height			
					Two month	Three month	Four month	Five month
Germination percentage	0.131	-0.086	0.123	-0.040	0.120	0.098	0.114	0.098
Germination value	-0.210	-0.146	-0.142	-0.042	0.137	0.139	0.197	0.176
Germination energy	0.163	-0.009	0.114	-0.019	0.124	0.024	-0.034	-0.039
Seed weight		0.579*	0.838*	0.615*	0.239**	0.316*	0.323*	0.333*
Seed length			0.527*	0.161	0.282	0.305*	0.275	0.284
Seed width				0.725*	0.287	0.335*	0.317*	0.314*
Seed thickness					0.152	0.252	0.282	0.298

***** Significant at 5 percent level.

Seed weight was found to be significantly and positively correlated with seed length (0.579), width (0.838) and thickness (0.615) of morphometric traits of seeds of the provenances. It was also found to be significantly and positively correlated with seedling heights at different stages. The correlation between seed weight and two, three, four and five month old seedlings was 0.239, 0.316, 0.323 and 0.333, respectively.

Seed length and seed width were significantly and positively correlated (0.527). The correlation between seed length and thickness was 0.161. Seed length had significant and positive correlation with height of three month old seedlings (0.305), while the correlation with height at other stages of seedling ranged from 0.275 to 0.284.

Seed width and seed thickness had strong and positive correlation (0.725). Correlation of seed width and two month old seedling height was 0.287. Significant and positive correlation was associated with seed width and height at three (0.335), four (0.317) and five (0.314) months old seedlings.

Seed thickness had positive correlation with height of seedlings at different stages. The correlation with two, three, four and five month old seedling height was 0.152, 0.252, 0.282 and 0.298, respectively.

4.3 PART III

4.3.1 Physical properties of wood

Physical properties of wood considered for investigation in the present study were heartwood percentage, density and fiber morphology. The properties were empirically investigated to identify the variation that associates with the provenances of *A. mangium* grown in Thiruvazhamkunnu. The materials for studying the properties were obtained by felling the trees that are representatives of each experimental plot of a replication in the trial plantation.

4.3.1.1 *Heartwood percentage*

Heartwood content of the provenances of *A. mangium* was estimated at different height levels of trees – 10 percent (base), 50 percent (middle) and 75 percent (top) of the total height of tree. The variation in heartwood, expressed as percentage, at each level of the height was compared between the provenances and summarized in Table 25. Obviously, heartwood percentage of the provenances decreased from base to top portion of tree stem. The overall mean heartwood percentage at base, middle and top portion of the tree was 69.23 percent, 62.53 percent and 51.76 percent, respectively.

Heartwood percentages of the provenances at the base portion of stem were found to be significantly different between the provenances, whereas at middle and top portion, the differences were not significant. At basal portion of the stem, Kerala seed source (81.33%), Oriomo (79.12%) and Pascoe River (73.41%) provenances had the highest heartwood percentage. The three provenances did not differ significantly from each other. Lowest percentage of heartwood at the base of tree was in Lake Murray provenance (58.67%). Tully-Mission Beach (67.69%), Arufi Village (65.70%), Kuranda (66.51%), Upper Aramia (66.61%) and Binaturi (64.36%) provenances were on par with Lake Murray provenance. The provenances having intermediate heartwood content in the present study were Claudie River (68.77%) and Balimo (69.28%). The two provenances differed significantly only from Kerala seed source, Oriomo provenance and Lake Murray provenance.

Table 25. Variaiton in heartwood percentage at different height levels of the provenances of *A. mangium*.

Provenance	Heartwood (%)		
	Base	Middle	Top
Tully-Mission Beach	67.79[bc]	58.39	52.58
Arufi Village WP	65.70[bc]	55.50	42.20
Claudie River	68.77[b]	63.95	48.33
Oriomo WP	79.12[a]	68.76	61.17
Kuranda	66.51[bc]	60.16	46.92
Pascoe River	73.41[ab]	70.00	60.22
Lake Murray	58.67[c]	56.39	49.78
Balimo	69.28[b]	67.95	47.99
Upper Aramia	66.61[bc]	57.20	52.83
Binaturi	64.36[bc]	61.40	47.05
Kerala	81.33[a]	68.10	60.27
Overall mean	69.23	62.53	51.76
P	0.001*	0.059[ns]	0.439[ns]

Mean values with similar superscript along the column do not differ significantly
* significant at 5 percent level and superscript 'ns' indicates non significant.

Highest heartwood content at the middle portion of tree was recorded from Pascoe River provenance (70.00%), followed by Oriomo (68.76%) and Kerala seed source (68.10%). At the top portion of the tree stem, Oriomo provenance (61.17%) had the highest heartwood percentage, which is closely followed by the Kerala seed source (60.27%) and Pascoe River provenance (60.22%).

Estimates of genetic parameters of heartwood content of the provenances at different height levels are given in Table 26. Genotypic coefficient of variation was higher than ECV at different height level of tree, except at top portion where GCV was 2.72 percent and ECV was 11.93 percent. Genotypic coefficient of variation for heartwood content at the base (8.48%), middle (6.49%) and top portion was found to be low. On the contrary, ECV was low at the base (4.11%) and middle (5.81%) portion of tree stem, while the top portion (11.93%) was found to be moderate.

Heritability of heartwood percentage was high at the base portion (81.01%), moderate at middle portion (55.51%) of stem and low at the top portion (4.95%). Similarly, genetic gain was high at the base (35.40%), moderate at the middle (16.62%) and low at the top portion (1.34%) of tree stem.

Table 26. Genetic parameters of heartwood percentage at different height levels of the provenances of *A. mangium*.

Height level	Coefficient of variation (%)		Heritability	Genetic
	Genotype	Environment	(%)	gain
Base	8.48	4.11	81.01	15.73
Middle	6.49	5.81	55.51	9.96
Top	2.72	11.93	4.95	1.25

4.3.1.2 *Density*

Basic density of the provenances was also studied at three different height levels of tree *viz.* base, middle and top portion, and the variation in density at each height level was compared between provenances. The result of the analysis is given in Table 27.

The average basic density at base, middle and top portion of the tree was 477.26 kg cm^{-3}, 468.29 kg m^{-3} and 530.39 kg m^{-3}, respectively. There were significant differences between the provenances at the three different height levels. Highest basic density at the base of tree stem was from Kerala seed source (533.45 kg m^{-3}) and the lowest was from Balimo provenance (396.69 kg m^{-3}). The density of the

Kerala seed source was significantly different from Balimo and Pascoe River (443.65 kg m^{-3}), while the rest of the provenances were on par with the Kerala seed source. Balimo provenance also differed significantly from Kuranda (524.43 kg m^{-3}) and Binaturi provenances (511.42 kg m^{-3}).

At the middle portion of tree stem, Upper Aramia had the highest mean basic density (405.93 kg m^{-3}). It differed significantly from Balimo (421.44 kg cm^{-3}), Pascoe River (427.97 kg m^{-3}), and Tully-Mission Beach (441.46 kg m^{-3}). Balimo and Pascoe River provenances had the lowest density. The provenances also differed significantly from Kerala seed source (497.78 kg m^{-3}).

Highest basic density at the top portion of tree was from Arufi Village (600.04 kg m^{-3}) and Tully-Mission Beach (585.02 kg m^{-3}). They did not differ significantly from each other. Lowest density was from Oriomo provenance (451.7 kg m^{-3}), followed by Claudie River provenance (466.61 kg m^{-3}) and Balimo provenance (471.16 kg m^{-3}). The three provenances differed significantly from the provenances of Tully-Mission Beach and Arufi Village. Provenances of Kuranda (561.76 kg cm^{-3}) and Kerala seed source (562.47 kg m^{-3}) differed significantly from Oriomo provenances. While, the provenances of Pascoe River (533.44 kg m^{-3}), Lake Murray (525.22 kg m^{-3}), Upper Aramia (542.88 kg m^{-3}) and Binaturi (547.73 kg m^{-3}) did not differ significantly from each other as well as with the aforementioned provenances.

The present study showed three patterns of variation in basic density for the provenances of *A. mangium*. First pattern of variation showed reduction in the density as it moved from base to middle and increased when it moved from middle to top portion of the tree stem (Figure 8A). The provenances that fall under this category were Tully-Mission Beach, Kuranda, Pascoe River, Lake Murray, Binaturi and Kerala seed source. The provenance that followed the second pattern of variation showed continued rise in the density from base to top (Figure 8B) and the provenances that exhibit the variation were Arufi Village, Claudie River and Oriomo provenances. The third pattern of variation showed highest basic density at the middle portion and reduced as it moved toward base and top portion (Figure 8C). Balimo and Upper Aramia followed this pattern of variation.

Table 27. Variation in basic density at different height levels of the provenances of *A. mangium*.

Provenance	Density (kg m^{-3})		
	Base	Middle	Top
Tully-Mission Beach	477.68^{abc}	441.46^{bc}	585.02^{a}
Arufi Village WP	476.89^{abc}	480.55^{abc}	600.04^{a}
Claudie River	467.92^{abc}	483.71^{abc}	466.61^{bc}
Oriomo WP	466.20^{abc}	470.63^{abc}	451.70^{c}
Kuranda	524.43^{ab}	476.32^{abc}	561.76^{ab}
Pascoe River	443.65^{bc}	427.97^{c}	533.44^{abc}
Lake Murray	474.23^{abc}	461.74^{abc}	525.22^{abc}
Balimo	396.69^{c}	421.44^{c}	471.16^{bc}
Upper Aramia	476.58^{abc}	488.04^{a}	542.89^{abc}
Binaturi	511.42^{ab}	476.30^{abc}	547.73^{abc}
Kerala	533.45^{a}	497.78^{ab}	562.47^{ab}
Overall mean	477.26	466.72	530.39
P	0.032*	0.046*	0.004*

Mean values with similar superscript along the column do not differ significantly.
* Significant at 5 percent level.

Genetic parameters of different provenances estimated in the study are given in the Table 28. In the present study, GCV of density at the base (11.35%) and top (14.23%) portion of tree stem was moderate, but it was found to be low at the middle portion (7.76%). Environmental coefficient of variation for the density was higher than GCV irrespective of the stem portion of trees. At the base and top portion of the tree height, ECV was moderate. The estimated ECV at the height was 10.91 percent and 17.78 percent, respectively. It was found to be low (7.96%) at the middle portion of the tree height.

Heritability of the trait ranged from moderate to high. It was moderate at the base (51.98%) and middle (48.71%) portion of the tree height, but when it moved to the top portion, heritability was found to be high (64.06%). Similarly, genetic gain was found to be moderate at the lower two height levels. It was estimated to be 16.85 percent at the base and 11.15 percent at the middle portion of the tree height. Genetic gain for basic density at the top portion of tree height was high (23.46%).

Table 28. Genetic parameters of basic density at different height levels of tree of the provenances.

Height level	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genotype	Environment		
Base	11.35	10.91	51.98	16.85
Middle	7.76	7.96	48.71	11.15
Top	14.23	17.78	64.06	23.46

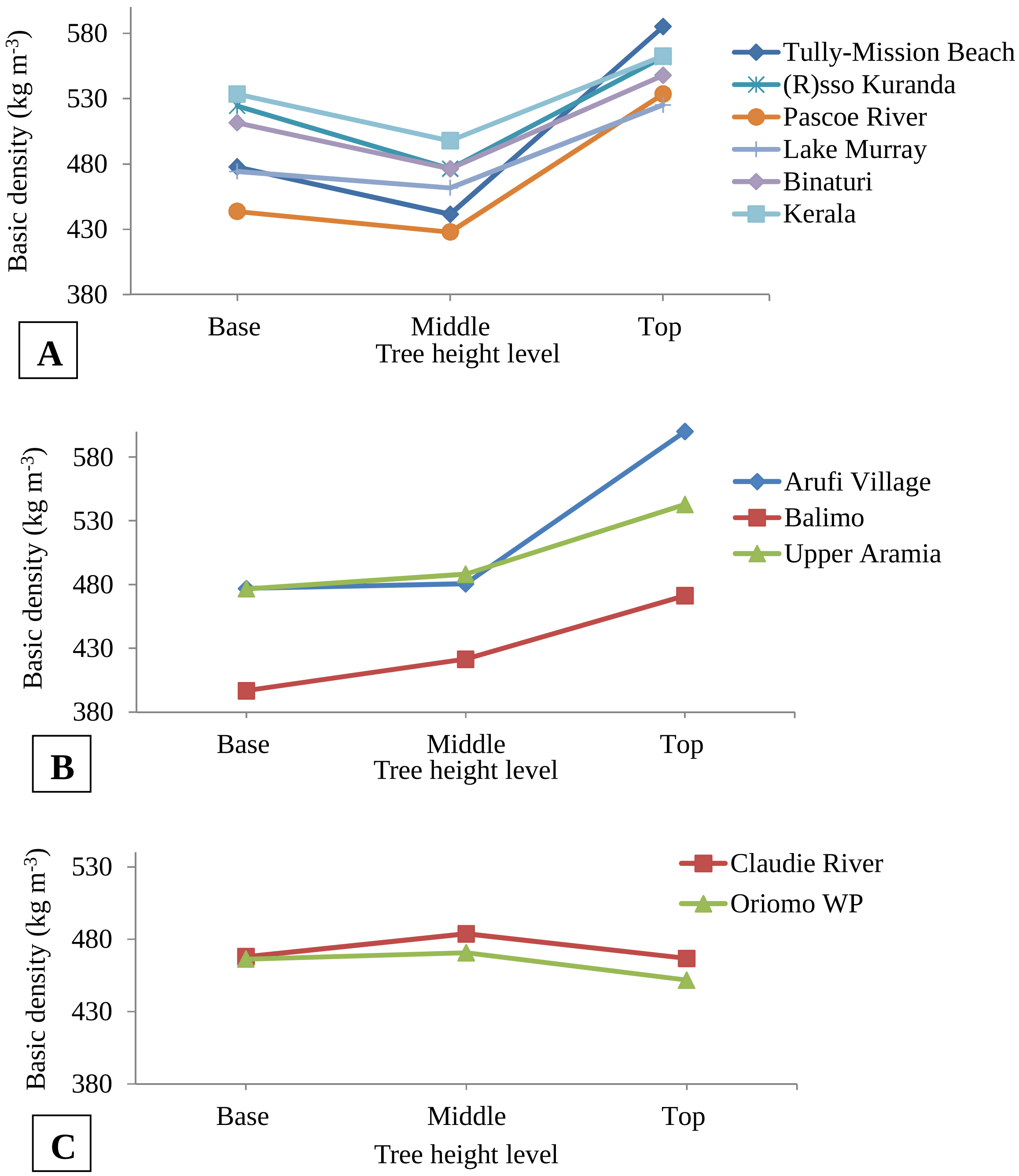

Figure 8. Variation in basic density at different height levels within tree of the provenances. (A) Lowest basic density was at the middle and increased towards the base and top portion of the tree height, (B) basic density increased from base to top portion, (C) highest basic density was at the midlle portion of the tree stem and decreased towards the base and top portion of the tree height level.

4.3.1.3 *Fiber morphology*

Fiber morphology of the provenances of *A. mangium* was estimated only from the disc obtained from the base portion of the tree height. Fiber traits like fiber length, diameter, lumen width and wall thickness were determined with the aid of Image Analyzer. Derived indices *viz.* slenderness ratio, runkel ratio, rigidity coefficient and flexibility coefficient, which have an implication in pulp and paper production, were also determined from the measurement taken for the fiber traits. Variation in the fiber characters and indices of the provenances are given in Table 29. Since, the fiber length, diameter, lumen width and wall thickness of the provenances deviated from normality, logarithmic transformation was done prior to statistical analysis.

Fiber length and diameter, lumen diameter and wall thickness were found to be significantly different between provenances (Table 29). In the present study, the provenances had an overall mean fiber length of 968.24 µm. Kuranda provenance had the highest fiber length (1091.05 µm). It differed significantly from other provenances. Shortest fiber length was observed from the provenances of Claudie River, Oriomo, Pascoe River and Balimo. They did not differ significantly from each other and the fiber length of the four provenances varied from 901.12 µm to 934.51 µm. The provenances of Claudie River and Balimo did not differ significantly from all the provenances, except Kuranda.

The overall mean fiber diameter of the provenances was 24.78 µm and lumen diameter was 21.08 µm. Balimo provenance had the highest (24.42 µm) fiber diameter. Fiber diameter of Binaturi (27.62 µm) and Oriomo provenances (25.99 µm) were on par with Balimo provenance. Kerala seed source had the lowest fiber diameter of 22.45 µm. The provenance was significantly different from Arufi village (25.48 µm), Oriomo, Binaturi and Balimo provenances. Balimo provenance had the largest diameter of lumen (24.42 µm) followed by Binaturi provenance (24.05 µm).

Lumen diameter of Oriomo provenance (22.06 µm) was on par with Binaturi provenance, while the rest of the provenances were significantly different.

In case of wall thickness of fiber, the overall mean of the provenances was 3.50 µm. Tully-Mission Beach, Arufi Village, Balimo, Upper Aramia and Binaturi provenances had the thickest wall among the provenances. The fiber wall thickness for the five provenances ranged from 3.53 to 3.95 µm. The five provenances did not differ significantly from each other. Claudie River provenance (3.20 µm) and Kerala (3.24 µm) had the thinnest fiber wall. They were significantly different from Tully-Mission Beach, Arufi Village, Upper Aramia and Binaturi provenances. The provenances of Upper Aramia and Binaturi also differed significantly from Lake Murray (3.32 µm), Pascoe River (3.34 µm), Oriomo (3.35 µm) and Kuranda (3.37 µm). The latter four provenances did not differ significantly from each other and they were on par with the provenances of Tully-Mission Beach, Arufi Village, Claudie River, Balimo and Kerala seed source.

Slenderness ratio, which is an index derived from the ratio of fiber length to fiber diameter, was found to be significantly different between the various provenances (Table 29). The overall mean of slenderness for the provenances was 40.87. The provenances of Kuranda, Lake Murray, Upper Aramia and Kerala seed source had the highest slenderness ratio. They did not differ significantly from each other and the range of slenderness varied from 43.06 to 47.06. Kuranda provenance and Kerala seed source differed significantly from all the other provenances, whereas the slenderness of provenances of Lake Murray and Upper Aramia were on par with all the provenances, except the slenderness ratio obtained from Balimo (33.76), Binaturi (36.06) and Oriomo (36.23). The latter three provenances i.e. Balimo, Binaturi and Oriomo provenances, had the least slenderness ratio in the present study.

Table 29. Variation of fiber morphology and fiber indices of the provenances.

Provenance	FL (µm)	FD (µm)	LW (µm)	FWT (µm)	SR	RR	RC (%)	FC (%)
Tully-Mission	981.83^{b}	24.54^{cd}	20.86^{cd}	3.62^{ab}	41.34^{b}	0.36	30.08	84.96
Arufi Village WP	984.27^{b}	25.48^{bc}	21.18^{cd}	3.95^{ab}	41.05^{b}	0.34	28.76	85.61
Claudie River	934.51^{bc}	24.48^{cd}	20.38^{cd}	3.20^{c}	39.29^{bc}	0.35	29.53	85.31
Oriomo WP	901.12^{c}	25.99^{abc}	22.06^{bc}	3.35^{bc}	36.23^{cd}	0.32	27.03	86.48
Kuranda	1091.05^{a}	24.16^{cd}	20.58^{cd}	3.37^{bc}	47.06^{a}	0.32	27.59	86.21
Pascoe River	911.49^{c}	23.57^{cd}	20.35^{cd}	3.34^{bc}	40.58^{bc}	0.34	29.00	85.50
Lake Murray	982.50^{b}	23.06^{d}	19.63^{d}	3.32^{bc}	43.79^{ab}	0.35	29.72	85.14
Balimo	930.16^{bc}	28.01^{a}	24.42^{a}	3.53^{abc}	33.76^{c}	0.30	25.40	87.30
Upper Aramia	996.88^{b}	24.13^{cd}	20.34^{cd}	3.75^{a}	43.06^{ab}	0.36	31.37	84.50
Binaturi	969.12^{b}	27.62^{ab}	24.05^{ab}	3.87^{a}	36.06^{cd}	0.34	28.80	85.60
Kerala	987.83^{b}	22.45^{d}	19.29^{d}	3.24^{c}	46.23^{a}	0.36	30.16	84.92
Overall mean	968.24	24.78	21.08	3.50	40.87	0.34	29.21	85.42
P	0.000*	0.000*	0.001*	0.000*	0.000*	0.149^{ns}	0.054^{ns}	0.075^{ns}

FL = fiber length; FD = fiber diameter; LW= Lumen width; FWT = fiber wall thickness, SR = slenderness ratio, RR = runkel ratio, RC = rigidity coefficient and FC = flexibility coefficient.
Mean values with similar superscript along the column do not differ significantly.
* significant at 5 percent level and superscript 'ns' indicate non significant.

In the present study, the ten provenances and one local seed source of *A. mangium* showed no significant differences in runkel ratio, rigidity coefficient and flexibility coefficient (Table 29). The average runkel ratio, an index derived from the ratio of double wall thickness of fiber to fiber length, of all the provenances was 0.34. Variation between the provenances ranged from 0.30 to 0.36. Tully-Mission Beach, Upper Aramia and Kerala seed source had an average runkel ratio of 0.36, while the provenance having the least runkel ratio in the study was Balimo (0.30).

Average rigidity coefficient which is expressed as percentage of the ratio of double wall thickness and fiber diameter of the provenances was 29.21 percent for the entire provenances. Highest rigidity coefficient (31.37%) estimated in the study was from Upper Aramia provenances and the lowest (25.40%) was from Balimo provenance.

Flexibility coefficient is also expressed as percentage of the ratio of fiber length to fiber diameter. The overall mean estimated for the provenances was 85.42 percent. The coefficient of the provenances varied from 84.50 percent to 87.30 percent. Highest flexibility coefficient estimated in the present study was from Balimo provenance and the lowest coefficient was from Upper Aramia.

The genetic parameters of fiber morphology were estimated and are represented in Table 30. Highest GCV among the various fiber morphology/ratios found in the study was in slenderness (45.10%) and lowest was in flexibility coefficient (2.75%). Environmental coefficient of variation was found to be the highest in runkel ratio (22.05%) and lowest in flexibility coefficient (3.27%). Heritability of trait was also found to be the highest in slenderness (87.08%) and the lowest heritability was found in runkel ratio (31.61%). Genetic gain of slenderness (86.69%) was the highest. Flexibility coefficient was found to have lowest genetic gain (3.65%) followed by runkel ratio (17.36%).

Genotypic coefficient of variation of fiber length was high (22.43%), but it was found to be moderate (10.28%) for ECV. Heritability (82.63%) and genetic gain (42.01%) for the fiber length was also high. Similarly for fiber diameter, GCV (30.15%), heritability (82.12%) and genetic gain (56.30%) was high, but ECV was moderate (14.07%).

Table 30. Genetic parameters estimated for fiber morphology and fiber indices of the provenances.

Character	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genotypic	Environment		
Fiber length	22.43	10.28	82.63	42.01
Fiber diameter	30.15	14.07	82.12	56.30
Lumen diameter	33.52	16.19	81.09	62.19
Wall thickness	24.35	14.79	73.05	42.86
Slenderness ratio	45.10	17.37	87.08	86.69
Runkel ratio	14.99	22.05	31.61	17.36
Rigidity coefficient	17.40	19.21	45.06	24.06
Flexibility coefficient	2.75	3.27	41.43	3.65

Lumen diameter (33.52%) and wall thickness (24.35%) also had high GCV. Environmental coefficients of variation of the traits were moderate and the corresponding values were 16.19 percent and 14.79 percent. Heritability of lumen diameter (81.90%) and wall thickness (73.05%) were also found to be high. Similarly, high genetic gain was observed for the two traits, 62.19 percent and 42.86 percent, respectively.

Runkel ratio and rigidity coefficient had moderate GCV of 14.99 percent and 17.40 percent, respectively. Environmental coefficient of variation was higher than

GCV in both the cases. The ECV of runkel ratio was high (22.05%), but for rigidity coefficient it was moderate (19.21%). Heritability of the traits was moderate for runkel ratio (31.61%) as well as rigidity coefficient (45.06%). Genetic gain of runkel ratio was moderate (17.36%), but it was high for rigidity coefficient (24.06%). Flexibility coefficient had low GCV and ECV, as well as low genetic gain (3.65%). Heritability of the trait was moderate (41.43%).

4.3.2 Correlation between growth and physical properties of wood

Inter-correlation between the growth attributes, density and fiber morphology were estimated using Pearson correlation and the results are furnished in Table 31. The correlation between growth attributes with density and fiber morphology was not significant. Correlation of DBH with density (-0.092), flexibility coefficient (-0.091) and lumen width (-0.022) was negative. The correlation of DBH with wall thickness, fiber length and fiber diameter was 0.108, 0.012 and 0.008, respectively. Correlation between DBH and fiber indices other than flexibility coefficient varied from 0.004 to 0.100.

Height had weak and positive correlation with density (0.115), fiber wall thickness (0.236), fiber length (0.181), fiber diameter (0.157) and lumen width (0.094). Correlation with fiber indices varied from positive to negative. Runkel ratio (0.183) and rigidity coefficient (0.167) had positive correlation with tree height of the provenances. Correlation of height with slenderness (-0.240) and flexibility coefficient (-0.166) was negative.

Correlation of volume with other attributes showed varied response. Correlation between the volume and density was -0.117. It also had negative correlation with fiber length (-0.050), slenderness (-0.125) and flexibility coefficient (-0.043). Correlation of volume with fiber diameter, fiber wall thickness and lumen width was 0.143, 0.129 and 0.109, respectively.

The correlation of density with fiber length, fiber diameter, lumen width and slenderness was significant. It was positively correlated with fiber length (0.412) and slenderness ratio (0.472), but negatively correlated with fiber diameter (-0.374) and lumen width (-0.350). The correlation of density with fiber wall thickness (-0.097) and flexibility coefficient (-0.084) was weak and negative. Correlation of density with runkel ratio and rigidity coefficient was 0.062 and 0.083.

Fiber length had significant correlation with slenderness ratio (0.671). Correlation of fiber length with fiber diameter, lumen width, fiber wall thickness, runkel ratio and rigidity coefficient was weak and negative. The correlation varied from -0.020 to -0.247. Flexibility coefficient had weak and positive correlation (0.020) with fiber length.

The present study showed significant and positive correlation of fiber diameter with lumen width (0.963) and flexibility coefficient (0.344). It was also significantly and negatively correlated with slenderness (-0.857) and rigidity coefficient (-0.344). Correlation of fiber diameter with fiber wall thickness and runkel ratio was 0.163 and -0.308, respectively.

Lumen width significantly correlated with all the fiber indices. The correlation with slenderness (-0.799), rigidity coefficient (-0.582) and runkel ratio (-0.550) was negative, but positively correlated with flexibility coefficient (0.799). Correlation of lumen width and fiber wall thickness was -0.109.

Significant and positive correlation of fiber wall thickness with runkel ratio (0.877) and rigidity coefficient (0.8620) was recorded for the provenances, but the correlation of wall thickness with flexibility coefficient was negative and significant (-0.862). It has weak and negative correlation with slenderness (-0.234).

Table 31. Correlation between growth attributes, density and fiber morphology of the provenances.

	Density@	FL	FD	LW	FWT	RR	SR	RR	FC
DBH	-0.092	0.012	0.008	-0.022	0.108	0.100	0.004	0.091	-0.091
Height	0.115	0.181	0.157	0.094	0.236	0.183	-0.24	0.167	-0.166
Volume	-0.117	-0.050	0.143	0.109	0.129	0.056	-0.125	0.043	-0.043
Density@		0.412*	-0.374*	-0.350*	-0.097	0.062	0.472*	0.083	-0.084
FL			-0.247	-0.210	-0.142	-0.023	0.671*	-0.020	0.020
FD				0.963*	0.163	-0.308	-0.857*	-0.344*	0.344*
LW					-0.109	-0.550*	-0.799*	-0.582*	0.582*
FWT						0.877*	-0.234	0.862*	-0.862*

FL = fiber length; FD = fiber diameter; LW = lumen width; FWT = fiber wall thickness; RR = runkel ratio; SR = slenderness ratio; RC = rigidity coefficient and FC = flexibility coefficient.
Superscript '@' indicates density was estimated at the base of the tree height.
*****significant at 5 percent level.

4.3.3 Mechanical properties of wood

For studying mechanical properties of wood, samples were collected from five randomly selected provenances *viz.* Arufi Village, Claudie River, Kuranda, Upper Aramia and Kerala seed source. The mechanical properties of wood studied in the present study were modulus of rupture (MOR) and modulus of elasticity (MOE) for static bending and maximum compressive stress (MCS) for compression parallel to grain. Moisture content of the wood at test was at an average of 23.70 percent. The results of the analysis and mean values are represented in Table 32.

The analysis of mechanical properties of wood *viz.* MOR, MOE and MCS, showed no significant difference between the five provenances. Overall mean of modulus of rupture estimated for the five provenances was 872.30 kg cm^{-2}. The variation between the provenances ranged from 672.84 kg cm^{-2} to 970.60 kg cm^{-2}. Highest MOR for the five provenances was from Kuranda and lowest was from Claudie River.

For MOE, the provenances had an overall mean of 123643.58 kg cm^{-3}. Modulus of elasticity varied from 105501.03 kg cm^{-2} to 166774.25 kg cm^{-2}. Arufi Village had the highest MOE and Kuranda was the least.

The result of testing the MCS showed that the strength of the provenances varied from 330.73 kg cm^{-2} to 431.34 kg cm^{-2}. The provenance having the highest and lowest MCS was from Arufi Village and Claudie River.

Estimates of genetic parameters of the mechanical properties of wood derived from the analysis of the five provenances are given in Table 33. Genotypic coefficient of variation of MOR (12.10%) and MCS (11.70%) were found to be moderate, while MOE had high GCV (21.55%). Environmental coefficient of variation was found to be low for MCS (9.20%) but moderate for MOR (15.45%) and MOE (18.24%).

Table 32. Static bending and compression strength of wood of the five provenances of *A. mangium* grown in Thiruvazhamkunnu.

Provenance	Static bending ($kg\ cm^{-2}$)		Compression strength parallel to grain ($kg\ cm^{-2}$)
	MOR	MOE	MCS
Arufi Village	966.69	166774.25	431.34
Claudie River	672.84	114392.10	330.73
Kuranda	970.60	105501.03	358.77
Upper Aramia	886.98	111375.10	403.13
Kerala	864.38	120175.42	407.55
Overall mean	872.30	123643.58	486.30
P	0.205^{ns}	0.080^{ns}	0.062^{ns}

Superscript 'ns' indicates non significant.

Maximum compressive stress had the highest heritability value among the tested traits. Heritability of MCS was high (61.79%), while MOR (38.02%) and MOE (58.28%) was found to be moderate. Genetic gain of mechanical wood properties was moderate. Genetic gain was found to be the highest in MOE (33.90%) followed by MOR (15.37%).

Table 33. Genetic parameters of mechanical properties of wood of the five provenances.

Character	Coefficient of variation (%)		Heritability (%)	Genetic gain (%)
	Genetic	Environment		
MOR	12.10	15.45	38.02	15.37
MOE	21.55	18.24	58.28	33.90
MCS	11.70	9.20	61.79	18.94

4.3.4 Correlation between growth, mechanical properties and fiber morphology

Pearson correlation between wood properties and growth attributes of five provenances are given in Table 34. No significant correlation between wood mechanical properties, growth traits and fiber morphology of the provenances were observed. The only significant correlation observed in the study was between the MOR and MCS of the mechanical properties of wood. The correlation between the properties was found to be positive (0.669).

The correlation of MOR with MOE was 0.219. Density and MOR had weak correlation (0.232). Correlation of MOR with height (0.246), DBH (0.148) and volume (0.064) was weak and positive. MOR had positive correlation with fiber length (0.247), but weak and negative correlation with fiber diameter (-0.345), lumen width (-0.276) and wall thickness (-0.164).

Correlation of MOE with MCS was 0.220. It also had positive and weak correlation with density (0.227), lumen width (0.144) and fiber diameter (0.071). The correlation of MOE with DBH, height, volume, fiber length and wall thickness was weak and negative. It ranged from -0.135 to -0.281.

Table 34. Correlation between growth traits, mechanical properties and fiber morphology of the five provenances.

	MOE	MCS	Density	DBH	Height	Volume	FL	FD	LW	FWT
MOR	0.219	0.669*	0.232	0.148	0.246	0.064	0.247	-0.345	-0.276	-0.164
MOE		0.220	0.227	-0.281	-0.182	-0.156	-0.226	0.071	0.144	-0.135
MCS			-0.104	0.228	0.104	0.138	-0.167	-0.043	-0.144	0.192

FL = fiber length; FD = fiber diameter; LW = lumen width and FWT = fiber wall thickness
*significant at 5 percent level.

Compression parallel to grain of the provenances had negative correlation with density (-0.104). It was positively correlated with growth attributes. The correlation with DBH, height and volume was 0.228, 0.104 and 0.138, respectively. Most of the fiber morphology, except wall thickness (0.192), had negative correlation with MCS. The correlation varied from -0.043 to -0.167.

4.3.5 Cluster analysis

Hierarchical cluster analysis can be used to assess relatedness and distance of any type of samples characterized by any type of descriptors (Peeters and Martinelli, 1989). In order to provide relatedness between provenances, hierarchical cluster analysis was performed using six traits *viz.* height of mature tree, heartwood content at the base, average basic density, fiber length, fiber wall thickness and fiber diameter. Dendrogram of the analysis is presented in (Figure 10).

The provenances formed two clusters at a rescaled distance of 25 units. The first cluster comprised of seven provenances *viz.* Arufi Village, Upper Aramia, Binaturi, Tully-Mission Beach, Lake Murray, Kuranda provenances and Kerala seed source. Second cluster comprised of Claudie River, Pascoe River, Oriomo and Balimo provenances. The first cluster at a distance of 16.85 units split into two clusters with Kuranda and Kerala separated from the rest to form one cluster. Further down the line it was seen that Arufi Village and Upper Aramia provenances remained together due to their similarity. The second cluster split into two clusters at a distance of 9.76 units. Claudie River and Pascoe River remained clustered, while Oriomo and Balimo split from the cluster at a distance of 4.25 and 9.76 units, respectively.

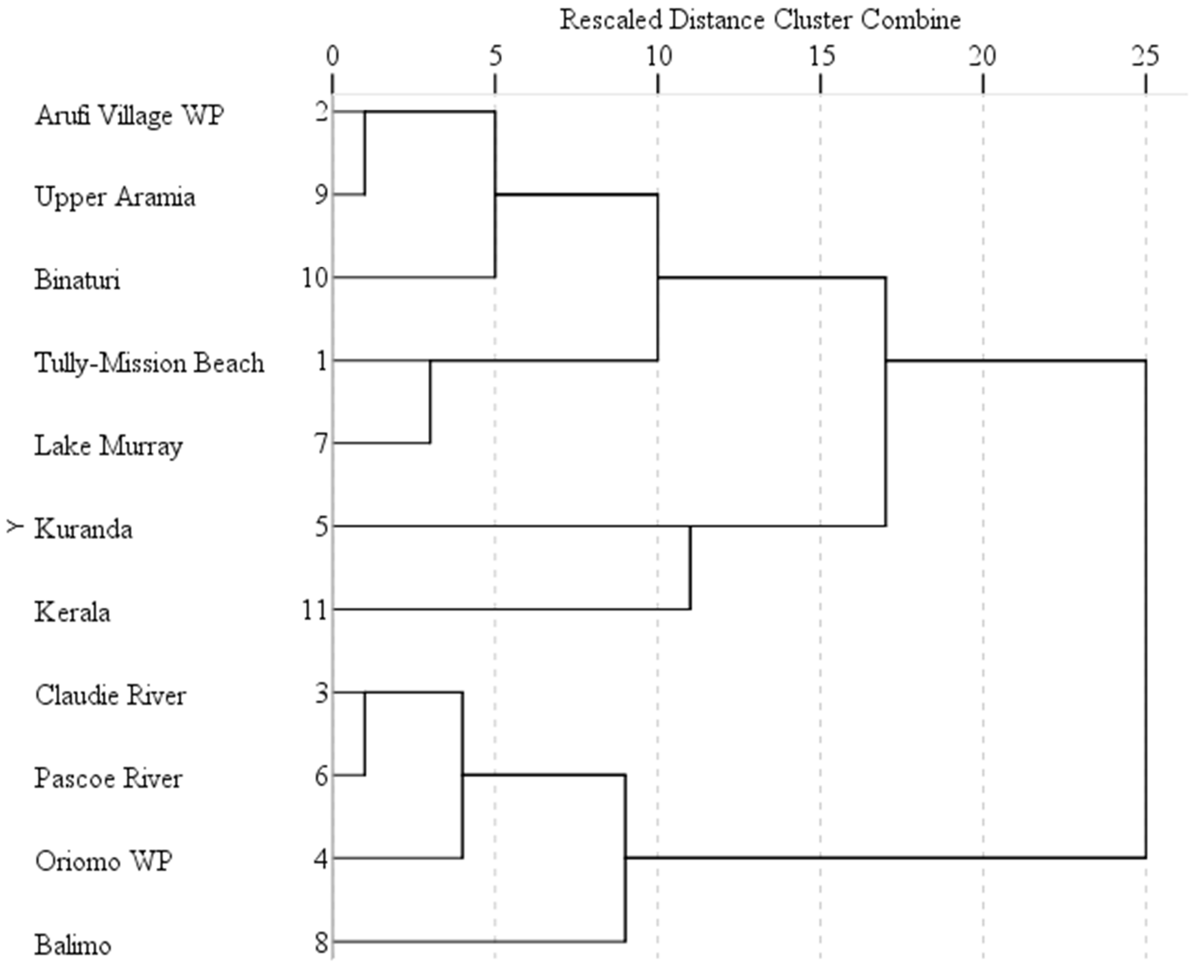

Figure 9. Dendrogram of the hierarchical cluster analysis of the provenances of *A. mangium* based on the six variates.

DISCUSSION

5. DISCUSSION

In the present study, eleven provenances including one local seed source were evaluated to identify the variations that exist in growth attributes and wood traits of *A. mangium*. The influence of the genetic and environmental factors on the selected characters as well as inheritance patterns of the traits was also examined to gain basic information for breeding purposes. The salient results are discussed hereunder.

5.1 PART I

The growth performances of the provenances were assessed in the trial situated in Livestock Research Station, Thiruvazhamkunnu. In the study, survival percentage of the provenances, DBH, height, volume and tree form were estimated. The stability of the provenances in the growth attributes were also determined using the secondary data of ten year periods of growth of the trial plantation.

5.1.1 Survival percentage

Whether a species is an exotic or native, the environment can induce changes in the individual behavior at the morphological and/or physiological level and such change is crucial for survival in heterogeneous and variable conditions (Gratani, 2014). Survival rate of a species is also influenced by the age of plantation. If there is high mortality rate for a species, it is stated that the necessity of breeding for higher survival rate outweighs the importance of breeding for volume per tree (Chambers and Borralho, 1997). But, the capability of a species to survive is often related with the provenance variation (Zobel and Talbert, 1984). The provenance that has a superior genotype for growth will show better survival ability as they are highly and positively correlated (Chambers *et al.*, 1996). Therefore, survival percentage is considered as one of the important selection trait.

Harwood and Williams (1992) had reported that the survival rate of different provenances of *A. mangium* at 1.5 to 3 years reduced to as low as 17 percent to 32 percent in Fiji and Bangladesh. Kurinobu *et al.* (2006) also reported that mortality rate of *A. mangium* increased rapidly after five years of planting if the plantation is left unthinned. In the present provenance trial no thinning has been carried out for the plantation, but all the provenances of *A. mangium* showed good survival percentage even after 13 years of growth. The survival percentage ranged from 59.26 percent to 96.30 percent. The variation between the provenances was not significant. Such high survival percentage highlighted the favorable climatic conditions of Kerala for the species and the suitability of all the provenances to the climatic condition. High survival percentage of the species irrespective of provenances and sites had also been reported in other places as well where *A. mangium* has been successfully introduced (Atipanumpai, 1989; Warren, 1991; Vincelette *et al.*, 2007).

5.1.2 Height, DBH and volume of the provenances

Plant grows in communities where they compete with neighbors for resources. Therefore, every changing environmental condition induces a response from the plant depending upon the genetic factor or independently through epigenetic nature of the species (Vaughn *et al.,* 2007). The characters used to identify its response to the environment depend upon the utilization point of view (Atipanumpai, 1989) and *A. mangium* is of interest because of its fast growing nature which is measured by diameter and/or height. Therefore, in the present study the performance of height, clear bole height, diameter and volume were the characters selected for growth attributes.

The overall mean of height and DBH for the 14 year old *A. mangium* in the trial was 20 m and 19 cm, respectively. On the contrary, the average height and DBH of the species at 6 to 10 years grown in different parts of Kerala was found to be at the range of 22 to 26 m for height and 35 cm to 39 cm for DBH (Dhamodaran and

Chacko, 1999). Another study conducted in West Java found that the growth of more than 10 years old *A. mangium* ranged from 20.03 to 22.93 m in height and 25.97 to 30.23 cm in DBH, despite being grown in an infertile soil (Nurhasybi *et al.*, 2009). Therefore, the growth of the provenances in the current trial was comparatively slow compared to the other studies.

The poor performance in the present site may be attributed to the poor soil condition. The site has an ultisol (Kunhamu *et al.*, 2010) which is a highly leached soil and usually lack phosphorous and other mineral nutrients (Gilberto *et al.,* 2015; Singh *et al.*, 2015). In addition to the deficiency of nutrients, the susceptibility to crusting, erosion and compaction were also being considered as major contributing factors for reduction of productivity in ultisols (Uexkull and Mutert, 1995). So, in the absence of external input of fertilizer and other management activities for the current trial plantation, it might have impacted the growth of the species. Slow growth of the site can also be observed from the fact that the report of 6.5 years old *A. mangium* plantation grown adjacent to the current trial with a planting density of 1250 trees ha^{-1} had an average height of 15.95 m and DBH of 14.93 cm (Kunhamu *et al.*, 2011) which is comparatively lower than the growth of 6 years old *A. mangium* reported by Dhamodaran and Chacko (1999). Instead, it was much more comparable with 5 year old *Eucalyptus urophylla*, another fast growing tropical species, grown in a degraded and infertile ferralitic clayloam soil. Mean height of *E. urophylla* in the infertile soil was found to be 13.1 m and DBH of 12.1 cm (Kien *et al.*, 2009). The importance of fertilizer application in tropical areas for *Acacia* species had been emphasized by Turnbull *et al.* (1998).

Moreover, the present study could not detect any significant difference, except for the height of the trees, between the provenances in growth attributes. The provenances that showed better performance in height were Kuranda, Arufi Village and Upper Aramia. The average height of the three provenances ranged from 21.27

m to 22.12 m. Oriomo (19.83 m), Balimo (19.58 m) and Binaturi (19.54 m) provenances features among the best as well as among the least performance in height. On the other hand, the provenances with poor growth in height were Pascoe River, Tully-Mission Beach and Lake Murray. They had mean height of 17.97 m to 18.61 m. Kerala seed source (19.06 m) also feature among the poor performer as it did not differ significantly from the latter provenances. Superiority of Kuranda and Oriomo of Papua New Guinea provenances in height, DBH and volume had been reported from the provenance trial in Vietnam, Sumatra, Zaire, etc. (Nghia and Kha, 1998; Warren, 1991, Khasa *et al.,* 1995; Sein and Mitlohner, 2011; Nirsatmanto, 2012).

The present finding is in contrary to most of the reports for provenance trials of *A. mangium* where significant variations were identified between provenances in growth attributes (Chittachumnonk and Sirilak, 1991; Harwood and Williams, 1992; Liang and Gan, 1991; Khasa *et al.,* 1995). However, it is not an exception. A provenance trial in Indonesia using 30 provenances showed no significant difference between them (Suhaendi, 1993). Low variation between provenances in *A.auriculiformis* had also been reported from Karnataka, India (Bulgannawar and Math, 1991). In both the reports the local provenance was also adjudged among the poorest performer. Similar finding of low variation between provenances had been reported in *Eucalyptus viminalis* and *Pinus radiata* and it was attributed to limited number of families included in the trial, problem faced during the initial stage of establishment or limited number of three replications (Varelides, 1996; Cappa and Pathauer, 2010). In the present study, no establishment problems that could have impacted the performances of the growth attributes were encountered. Moreover, limited number of families being represented during the collection of seeds is not likely to be the cause. The most probable reason could be that under poor site conditions, provenances were not able to exhibit their potential. This will have a bearing on their stress tolerance mechanism. Rochon *et al.* (2007) also reported that in *Guazuma crinite* the variations between provenances were most pronounced in the site where there was rapid growth.

Clear bole height among the provenances was also found to be relatively low and did not differ significantly from each other. The overall mean of the height estimated during the year (14 years old) was just 9 m which corresponded to 46 percent of the total height of trees. Sulaiman and Lim (1993) had also reported low clear bole height of 4 m to 9 m for 5 years old *A. mangium* having an average height of more than 20 m. The reason for short clear bole height is that *A. mangium* do not self-prune easily like *Eucalyptus* species (Atipanumpai, 1989) and the present trial plantation was not subjected to any kind of silvicultural management, except for occasional weeding. So, in the absence of artificial pruning it is obvious to have short clear bole height. But it is at the higher end, when compared with 8 year old *Melia azedarach* which had an average of 2.13 m clear bole height (Meena *et al.*, 2014). Clear bole height in the present study was found to have higher ECV (29.28%) than GCV (17.39%), so it is important that proper silvicultural management practices are followed for the provenances to obtained good bole height.

Secondary data, starting from five years till it attained the age of 14 years, for the provenances maintained by the AICRPAF showed that mean annual increment of DBH was found to be the highest at 5 years with an average of 2.83 cm and gradually reduced with age to 1.36 cm at 14 years. From the finding it can be presumed that the maximum MAI in volume of the provenances will be within 6 to 9 years as reported by Mead and Miller (1991) and Warren (1991). This is one of the important aspects of *A. mangium* being considered for plantation programmes. The fast growing nature make the species reach culmination point very early for fixing the rotation age and thus reducing the time for harvest.

The MAI reported by Kha and Nghia (1991) for the species (2.4 cm at 8 years) is comparable with the present study for the corresponding age, but it was higher than the MAI of DBH (1.01 cm to 1.29 cm at 8 years) reported by Patil *et al.* (2012) for *A. mangium* and clones grown in red shallow soil of Karnataka, India. In the present study, the local seed source (3.11cm) and Oriomo provenance (3.07 cm) had the highest MAI of DBH at 5 years. Oriomo provenance continued to perform better than the other provenances till the 14^{th} year, while the local seed source showed varied response.

Determining and understanding the nature, cause and amount of variation is an important step for tree improvement (Awang and Bhumibahmon, 1993). To identify the genetic control and the magnitude of variation as a result of genetics and environment, their broad sense heritability, GCV and ECV had been worked out for the growth attributes and other traits as well. In terms of magnitude of variation contributed by the genotype, GCV of height (15%) and DBH (9.99%) were lower than volume (38.57%) in the present study. Cornelius (1994) had reported that the individual tree volume will have the highest level of additive GCV than the other growth attributes. It was further reported that the GCV of other traits tend to be below 15 percent. Concurrently, the GCV of height and DBH in the present trial were 15 percent and 10 percent, respectively. The present study showed that GCV was higher than ECV (12%) for height, while ECV of volume (29%) and DBH (29%) were higher than GCV. Clear bole height was also found to be more influenced by the environmental factors. Similar finding was reported by Meena *et al.* (2014). Genetic control, based on broad sense heritability, of height in the present study was high (63%) moderate for stand volume (49%) and low for DBH (26%). The contribution of genetic to the total variation for clear bole in the present trial was also low (26.08%). Higher genetic control over height than the volume and DBH is in agreement with the report of other studies. After compilation and analysis of 67 published literatures of forest tree species, Cornelius (1994) reported that height tends to have higher heritability than DBH and volume. In Virginia pine, it was also reported that height has higher heritability (59%) than DBH (33%) for eight years old trees (Meier and Goggans, 1977). Svensson *et al.* (1999) also found higher heritabilities for height (65% to 84%) in loblolly pine than DBH (19% to 37%) and volume (0.43% to 0.61%). Similar finding of higher heritability for height (28%) than DBH (14%) has been reported for *E. cladocalyx* (Mora *et al.*, 2009). However, there are various reports where DBH had higher heritability than height (Susanto *et al.*, 2008; Kien, 2009; Cappa and Pathauer, 2010). Study conducted using composite seedling orchard of *A. mangium* in Indonesia also found that individual narrow sense heritability of DBH (20%) was the highest followed by height (8%) and volume (4%; Nirsatmanto, 2012). Nevertheless, present finding of high heritable nature of height and higher genetic influence than the environment on the trait favored the selection based on the trait for the provenances of *A. mangium*. The expected genetic gain was also found to be high (25%) for height. Genetic gain for volume (56%) was also high, moderate for clear bole height (18%), but low for DBH (10%).

Moreover, the analysis of stability using AMMI model showed that there was no significant interaction between genotype × environments in DBH. This implies that the relative performance of the provenances in term of growth of DBH will remain unchanged irrespective of the environment that prevails in the site. The most stable provenances in terms of DBH were Kuranda and Arufi Village (Figure 3). The two provenances also happened to be among the best performing provenances in most of the parameters studied in the present investigation, therefore they can be recommended for Kerala condition.

5.1.3 Tree form characters and branching habit

Tree form and branching habit affect the final product of wood (Zobel and Talbert, 1984). Undesirable tree form and branching habit decreases the volume, economic value of tree and increases the price of timber manipulation and transportation (Codesido and Fernandez-Lopez, 2008). Stem taper, which is expressed by the ratio between stem diameter at breast height and at a higher level, are important for volume production and properties such as wane and spiral grain (Ehrenberg, 1970). Therefore, improving of stem form and branching characteristics had been stressed as a critical part of breeding strategies for tree improvement program (Cameron *et al.,* 2012). Such program figures most prominently in the breeding goal of conifer species. Nevertheless, its importance is felt for the hardwood and fast growing species. Therefore, to assess the tree form characters and branching habit, visual scoring system was employed and each tree was evaluated for the provenances.

In the present study, there was no statistically significant difference between provenances in tree form and branching habit. Similarly, univariate analysis showed no significant difference between provenances for the percentage of good axis, straight tree and light branched trees. The average number of trees having good axis persistence (52%), straight tree (73%) and light branched tree (63%) were high. Moreover, trees of the provenances had good taper of stem (0.87), but no significant differences between provenances. The present finding showed that majority of trees of the provenances has good tree form and branching habit. This aspect should be utilized in breeding programme so that it will improve tree form. In turn, the quality and economic value of the timber will increase. In a provenance trial of *Gmelina arborea,* Indira (2006) also reported that no significant differences exist in axis persistence, stem straightness and branch thickness as well as in the percentage of straight trees and light branched trees. However significant differences were observed for good axis persistence at one site. The result showed that 57.92 percent and 60 percent of the total number of trees of *G. arborea* had good axis persistence and light branched trees, respectively, but the species was found to have low proportion of trees (12.11%) having straight stem. Stand quality assessment of *Tectona grandis* also showed that no much difference exist between the Chittagong and Sylhet study area in branching habit and stem straightness, but the differences in axis persistence were found to be significant (Mollick *et al.,* 2005). The percentage of trees having light branched were found to be high (70%) in the study and about 10 percent to 20 percent of trees tend to posses complete persistence on both the sites. In a provenance trial of *Grevillea robusta*, Harwood *et al.* (2002) also reported that stem straightness and axis persistence were found to be significantly different between 23 provenances. However, they cautioned that their performance could not be established with confidence, because many of the provenances were poorly represented in the trial, with fewer than five families tested. Therefore, the present finding is in alignment with many of the studies that showed that variation in tree form is low.

Zobel and Talbert (1984) have strong opinion on the highly heritable nature of tree form, especially stem straightness. It stated that, because of the strength of its inheritance, it was often possible to make enough gain in straightness even at the first generation of intensive selection, while branching characteristics were much more strongly influenced by the environment and might result in modest gain. Similar view of strong environmental influence on branching habit had been endorsed by Vargas-Hernandez *et al.* (2003). It was stated that modest response in branching traits were expected from selection at age 12, because of the weak genetic control observed for these traits in the field. The present study showed that straight trees (39.09%) and stem taper (44.84%) of the provenances of *A. mangium* were moderately heritable. Similar finding had been reported in other species as well. A study to determine genetic parameters for straightness of stem of *E. cladocalyx* showed that stem straightness had moderate heritability (40%; Vargas-Reeve *et al.* 2013). In loblolly pine, heritability of stem straightness was moderate to high (26% to 51%) for open pollinated families (Shelbourne and Stonecypher, 1971). Heritability of stem crookedness for *Dalgergia sissoo* was also reported to be 42 percent and 65 percent at two different sites of Pakistan, Daphar and Pirawala plantation (Vidakovic and Ahsan, 1970). Stem straightness of *Pinus taeda* had low heritability at 1.5 years (2 to 8%) which increased to moderate (16% to 33%) with age (Gwaze *et al.,* 1997). This indicates that the straightness of tree in the present study is strongly influenced by genes and there are potentials for further improvement through selection.

On the contrary, low heritability (27.59%) of good axis persistence was found to be associated with the provenances of *A. mangium* in the present study, while light branched trees had moderate heritability (46.11%). Harwood *et al.* (2002) also found low heritability (11%) of axis persistence. Higher heritability of branching habit (29%) compared to stem form (22%) had been reported by Volker *et al.* (1990). Moderate heritability (41% to 42%) for branching habit comparable with the present finding was reported in Douglas fir (Vargas-Hernandez *et al.,* 2003). Environmental coefficient of variance for tree form and branching traits was greater than genetic coefficient of variance in the present study and the genetic gain expected for good axis persistence, straight trees and light branched trees were moderate but low for stem taper (Table 10). Since the heritability as well as the GCV were relatively low for good axis persistence, it is advisable to conduct regular pruning and other tending operation. Multiple stem is one of the characters for undermining the good axis persistence and this can be routed at the initial stage of growth by singling.

When stem straightness of *Pinus taeda* were subjectively assessed using relative straightness scoring system with a scale of 1(best) to 6 (worst) and compared with sweep, a product grading standard, it was observed that genetic differences were inflated in one test which had exceptionally straight trees and undervalued at a second test which had extreme variation in bole straightness (Williams and Lambeth, 1989). They further added that use of such relative score will give suboptimal response to multiple trait index selection if sites influence the degree of trait expression. Therefore, the estimated mean and genetic parameters in the present study for tree form and branching habit need to be further confirmed by testing in different sites.

5.2 PART II

Seeds of the open pollinated parents were collected from the trial plantation and used for testing the progeny in the nursery. Morphometric traits of seeds, viability, dormancy, germination parameters were also evaluated for variation between provenances. Understanding the pattern of variation in the characters is important, because of their implication in the performances of the seedling.

5.2 Morphometric traits of seeds

Seed is the reproductive organ that plant relies upon for multiplication and dispersal. Seeds morphometric traits can vary depending upon the growth form and dispersal mode of plants within different communities (Zhang, 1998; Bonfil, 1998). Few studies have been reported for the variations of morphometric traits of seeds between provenances of *A. mangium*. In the present study, 100 seeds were evaluated for morphometric traits from the ten provenances and one local seed source.

Variations of morphometric traits of seeds between the provenances in the present study were found to be significant. Highest seed weight (332 mg), width (2.68 mm) and thickness (1.57 mm) were observed in Arufi Village provenance of Papua New Guinea. It differed significantly from rest of the provenances. On the contrary, the Kerala seed source produced the lowest mean value for all the morphometric traits of seeds. The variation in the traits for the Kerala seed source was found to be significantly different from all other provenances, except for seed thickness. Seed thickness was found to be more or less similar with Tully-Mission Beach, Oriomo WP, Balimo, Upper Aramia and Binaturi. The studies of Salazar (1989) and Adjers and Srivastava (1993) also revealed that Papua New Guinea provenance usually had larger seed size than the provenances of Queensland and Indonesia. But in the present study, apart from Arufi Village provenance of Papua New Guinea, provenances from Queensland too, tend to have larger seed size (Table

13). This was most pronounced in the seed length. The seed length was found to be the highest from Pascoe River (4.22 mm) and Tully-Mission Beach (4.20 mm) provenances of Queensland. Large size seeds have the advantages of higher seed germination and seedling establishment, while smaller seeds have the advantages of escaping animal and bird predation and forming soil seed banks and exhibit greater potentiality in vegetation renewal (Donaldson *et al.,* 2014). Therefore, the competitive advantage for renewal of vegetation communities can be modulated through the seeds depending upon the size of the seeds and the environmental conditions (Susko and Cavers, 2008). Seed size also play an ecologically important role during stress condition and such information provides a biological basis for the conservation and reintroduction of many species (Ramirez-Valiente *et al.,* 2009).

In terms of genetic variation, seed morphometric traits had low GCV as well as ECV. Seed weight had the highest GCV (10%) followed by seed width (4%), thickness (4%) and length (3%). Shu *et al.* (2012) also reported that seed weight had the highest variation in the morphotmetric traits in *Magnolia officinalis.* Environmental coefficient of variation of the traits in the present study was much lower (less than 2%; Table 14). The contribution of genetic to the total variation was very high. It was more than 90 percent in all the traits. Similar finding had been reported in *Cordia africana* (71% to 98%; Loha *et al.,* 2006) and *Senna siamea* (69% to 83%; Takuathung *et al.,* 2012). The genetic gain expected from 5 percent selection intensity for the provenances was also high for all the morphometric traits, except for the seed width, which was found to be moderate (20%). Highest genetic gain was expected in seed weight (56%).

However one must note that seed morphometric traits are strongly controlled by the maternal effect (Roach and Wulff, 1987; Gonzalez-Rodriguez *et al.*, 2011) which can be further modified by the prevailing environmental factors like availability of nutrient, moisture, temperature, latitude or the developmental stage of the plant

(Zhang, 1998; Uniyal *et al.*, 2000; Loha *et al.*, 2006; Rawat and Bakshi, 2011; Shu *et al.,* 2012). The variation in the traits influenced the performance of seedlings. Bonfil (1998) reported that seedlings originating from larger seeds were better equipped to confront stress at an early stage as well as at the end of the growing season in *Quercus* species. Seedling height, diameter, leaf area and biomass were also found to be profoundly affected by the seed size in the study. Therefore, the variation in the production of the seed has a functional relationship with the performances of seedlings (Green and Juniper, 2004; Quero *et al.,* 2007) and reflects the response of a species to maximize their potential fitness and survival in the environment (Zhang, 1998). But such functional relationships haven't been studied in exotic *Acacia* species which has been introduced and acclimatized in the country for more than decades. Understanding of such relationship will throw a light into its greater functional and ecological roles. It will also give an insight into its invasive capabilities, because *A. mangium* had been reported to colonize degraded and disturbed forest land, displacing the native species in Borneo Island (Davies and Becker, 1996). But the threads of the species, in general *Acacia* species, colonizing a forestland are significant only when there is abundant light, whilst in intact forest or disturbed but periodically wet habitat, its thread is limited (Osunkoya *et al.,* 2005; Nghiem *et al.,* 2015).

5.2.2 Viability, dormancy and germination

Dormancy assays are based on seed germination, which is the result of the balance between the degree of dormancy and the capacity of the embryo to overcome dormancy (Bentsink and Koornneef, 2008). Dormancy and germination are complex traits that are controlled by a large number of genes, which are affected by both developmental and environmental factors (Koornneef *et al.,* 2002). It has been defined as the incapacity of a viable seed to germinate under favorable conditions (Bewley, 1997).

Before the experiment was conducted for determining the dormancy and germination test, viability of seeds was assessed using tetrazolium chloride solution. Viability of the provenances was found to be high. It ranged from 93 percent to 100 percent. High viability of the provenances can also be noticed from the high germination capacity. In the germination test, the control seeds failed to germinate, while seeds that were treated with hot water were able to germinate when kept under the same condition as control. This together with high germination capacity of the control seeds indicated the presence of dormancy (Table 17). It also implies that use of hot water for treatment of seeds induced a change to the treated seeds. Baskin (2003) had reported that seed coat of *Acacia* species possess lignified malphigian cells called lens, which made the seed impermeable to water. The lens can be dislodged by stress or after prolong soaking in water (Baskin, 2003; Warrag and Eltigani, 2005). Therefore, when the seeds of *A. mangium* were treated with hot water, it probably induces a stress and dislodged the lens, which in turn facilitates the passage of water for inducing germination process. On the other hand, absence of stress or any other mechanical means kept the lens intact and prevent the imbibitions of water. Therefore, the control which were devoid of any stress had high water impermeability and, thus, failed to germinate i.e. they have physical dormancy (Baskin *et al.,* 2000). This finding confirmed that *A. mangium*, like most of the other *Acacia* species, has physical dormancy.

Permeability and impermeability of water is a factor that depends on the level of lignifications (Kelly *et al.,* 1992) and how tightly the cells are packed in the palisade layers (Baskin *et al.*, 2000). Therefore, it may not exclusively preclude the imbibitions of water. Moreover, water uptake for germination is triphasic. A rapid initial uptake (phase I, i.e. imbibitions) followed by a plateau phase (phase II). A further increase in water uptake (phase III) occurs only after germination is completed (Manz *et al.,* 2005). Therefore, even though there is absence of germination, the control showed slight increased in seed mass (Table 16**)** which was not sufficient enough to induce germination. Similar finding of minute increased in seed mass, despite being dormant, had been reported in three other *Acacia* species (Venier *et al.*, 2012).

Germination traits of seeds of all plants are influenced by the provenance (Keller and Kollmann, 1999). Substantial variations in germination had been reported for *Acacia* species. *Acacia mangium* usually has high germination percentage. It was reported to be much higher than *A. auriculiformis, A. aurlacocarpa* and *A. crassicarpa* and *A. oerfota* (Indira, 1999; Abari *et al.,* 2012). The germination percentage of the provenances in the present study was also found to be high. It ranged from 72 percent to 94 percent. The analysis of the germination related parameters of the provenances showed significant difference between them, except for germination capacity. Germination capacity followed the pattern of viability and did not differ significantly between the provenances. Lake Murray provenance of Papua New Guinea was the best performing provenance in almost all the parameters observed for germination. It also had the shortest day (7.25 days) for germination to reach 80 percent or more from the total number of seeds germinated. It was closely followed by Claudie River (9 days) and Balimo (9.50 days) provenances. They outperformed Lake Murray provenance in germination energy. On the other hand, Kuranda and Pascoe River of Queensland were among the poor performer in most of the parameters. However, they had shorter germination period than Tully-Mission Beach, Arufi Village and Upper Aramia provenances. Large differences between provenances for germination percentage were also reported in many other species (Keller and Kollmann, 1999; Uniyal *et al.,* 2000; Bischoff *et al.,* 2006; Shu *et al.,* 2012).

Germination test of the present study showed that genetic influence was higher than the environment for the germination traits of the provenances. Highest GCV was associated with germination value (25%) and germination energy was found to be the least (6%). Heritability also ranged from moderate (55.84%) to high (80.67%)

for the parameters. Understanding the genetic parameter is an important step for selection of provenances, because the right choice of selection of provenances is as important as pretreatment (Uniyal *et al.,* 2000). The high genetic control of the species for the traits make the presumption confident that the provenances of Lake Murray, Claudie River and Balimo will performed better in the field. Therefore, the three provenances should be used if germination is likely to be a concerned for regeneration of the species in the field.

High stability in the germination traits can allow reliable prediction of between-provenance difference in the field (Bischoff *et al.,* 2006). Likewise, the better performances of Lake Murray provenances in the present study for the germination traits were observed to perform better in the nursery in height (Figure 4) and also expected the same in the field as well. Another important factor that influences the germination is the variation in the seed size. However, in the present study, it was found to be positively and significantly correlated only with germination period and seed weight and width. Similar finding had been reported for *A. nilotica*. Larger seed size of *A. nilotica* was found to be associated with higher germination velocity and percentage (Jones and Sanders, 1987). But, the effect on germination traits with the rest of morphometric traits in the present finding was found to be weak. The independence of germination traits to the seed traits had also been reported in other species including shrubs and herbs species (Zhang and Maun, 1990; Shipley and Parent, 1991; Eriksson, 1999). However, in the present study seed size classes were not maintained this could have failed to detect its effect.

5.2.3 Seedling growth

In the present study, the seedling height at two months did not differ significantly between the provenances, but after two months, the traits showed significant difference between them. However, no significant differences were observed in collar girth in all the stages. Indira (1999) also reported low variation for the species in the seedling girth as well as for height of nine provenances of Papua New Guinea, when provenance trials were conducted in Kerala, India. The overall mean of seedling heights of the provenances found in the present study increased from 10.87 cm at two months to 21.40 cm at three months of growth after sowing and collar girth ranged from 1.62 mm at two months to 3.31 mm at three months. Lake Murray provenance was one of the provenance that performed best in the study, while the local seeds of Kerala showed poor performance throughout the period (Figure 4). The growth in height of the ten provenances was much better even if it compared with the performance of seedlings of *A. mangium* that were inoculated with different types of mycorrizhal fungi (Ghosh and Verma, 2006). But the treated seedlings were better than the local seed source used in the present study.

No difference was observed for RGR between the provenances. Low variation in RGR had also been reported for other species by Shu *et al.*(2012). Takuathung *et al.* (2012) also reported low variation for RGR in *Magnolia officinalis.* The result of RGR also showed that the highest growth rates of seedling of all the provenances were observed within 60 days of growth. Thereafter, as the seedling grew older, the growth rates tend to decrease, but it does not follow any particular pattern. The decline in growth rate is in accordance with the reports for other species (Turnbull *et al.,* 2012).

The provenances had high heritability for height and moderate for girth. Heritability of height and girth was 72 percent and 45 percent, respectively. This is in conformation with the earlier findings that height and girth were substantially under the genetic controlled (Uniyal *et al.,* 2000; Loha *et al.,* 2006; Shu *et al.,* 2012; Takuathung *et al.,* 2012). It is also evident from the observation that the provenances which showed better performances during the initial stage of growth continued to perform better even at the later stage of the study period. Such consistency should be related to growth in the field, if it followed the trend, it could be a very important initial selection mechanism (Salazar, 1989) and grading of seedlings based on the two traits would be a good viable option for *A. mangium.* More emphasize should be given on height for grading, because of its higher genetic control compare to collar girth as well as higher genetic gain of height (16%) than girth (5%). Higher genetic control over height than girth for the species at 18 to 30 months was also reported by Atipanumpai, 1989. Kien *et al.* (2009) also found that, in *Eucalyptus urophylla*, heritability of height was higher than DBH below the age of two years.

On the contrary, low GCV was associated with height and girth for the provenances of *A. mangium*. Out of the two traits, seedling height had higher GCV than the collar girth of the provenances (Figure 7). This further strengthens the recommendation of grading of seedlings based on height. The GCV of height ranged from 4.51 percent to 9.08 percent and 3.54 percent to 4.47 percent for collar diameter. This was much lower than the GCV of height (12.41% to 15.35%) and girth (19.72% to 23.19%) reported by Indira (1999) for 9 to 12 months old provenances from Papua New Guinea. However, in the present study, genotypic coefficient of variation increased with age for both the characters.

Another important finding of the study was the strong correlation between morphometric traits and seedling growth (Table 24). Seed weight was found to be strongly correlated with the height of seedlings at all stages of the study period. The correlation coefficient increased from 0.239 at two months to 0.333 at five months. Similarly, seed width also had significant correlation (0.314 to 0.335) with seedling height after two months of growth, but it decreases with increased in months. This highlights the importance of choice of seed size during seed collection, irrespective of whether the information of the parent materials is available or not. The correlation of seed length and thickness with seedling height was relatively weak, but the importance of the two traits cannot be undermined, because of their strong correlation with seed weight (0.579 and 0.615, respectively). Therefore, it is important to ensure that large sized seeds are collected during collection of seeds for various purposes. This will have great implication when the species are to be used for reclamation of wasteland like *Imperata cylindrica* infested area, because small differences in the performances are greatly magnified under competitive conditions (Weiner, 1990). Having said that, additional research is warranted on application of such finding in the field where competitions and unpredictable circumstances prevails.

5.3 PART III

In the present study, mechanical and physical properties of wood were estimated for the provenances of *A. mangium*. The samples were collected from the field after felling the trees. Physical properties like density and heartwood proportion were estimated at different height levels, while fiber diameter was estimated from the base of tree height. Mechanical properties of the wood were tested for five randomly selected provenances. The properties included in the estimation were static bending and compression parallel to grain.

Properties of wood vary from one species to another as well as within an individual. Differences in age and growth habitat also influence the properties of wood (Bhat *et al.,* 1985; Zobel and Talbert, 1984; Zziwa *et al.*, 2006). Provenance variation had also been recorded in many of the studies conducted for *A. mangium*. Such differences need to be considered while selecting a provenance for improvement in wood properties of a species, because the ultimate aim of breeding a forest tree species is for higher production of wood materials. *Acacia mangium* has a moderately durable wood (Jusoh *et al.*, 2014). It can be used for many mechanical purposes, but more importantly they are used for pulp and paper production (Griffin *et al.,* 2011). The main sources of pulpwood in the future for Asia are expected to be from *Acacia* and *Eucalyptus* plantations (Paavilainen, 1998).

5.3.1 Heartwood percentage

Depending upon the purpose of end use of wood materials the desired sapwood-heartwood percentages may vary. High percentage of heartwood may be a more desirable character for used as solid wood, while it may not be the case if the end use is for pulp and paper production because of the presence of higher extractives (Lourenco *et al.*, 2008). So determining the variation in heartwood associated with the provenances is necessary.

The result of the present study showed that heartwood percentage decreased as it moved from basal portion to the top portion of the stem in all the provenances. The overall mean percentage of heartwood at base (10% height level), middle (50% height level) and top (75% height level) was found to be 69.23 percent, 62.53 percent and 51.76 percent, respectively. This is comparable with the study conducted for the species in Kerala. The overall mean heartwood percentage of *A. mangium* grown in the state was reported to be 63 percent at 25 percent height level, 57.1 percent at the middle and 49.5 percent at the top portion for 10 years old trees (Dhamodaran and Chacko, 1999). The average content of heartwood for the present study is also comparable with *A. melanoxylon* where heartwood represented 64 percent of the stem cross sectional area up to 50 percent of the total tree height (Knapic *et al.*, 2006), but much higher than *Pinus pinaster*, which is the main timber species in Portugal, where heartwood represented only 17 percent of the stem up to 50 percent of total tree height (Pinto *et al.*, 2004). The decline in the heartwood content as it moved from base to top portion in the present study is not as steep as the decline observed in *E. regnans.* For the species, heartwood percentage was found to be 67.41 percent at the breast height, but substantially reduced to 30.24 percent in the percentage when it attained 60 percent of the total tree height (Githiomi and Dougal, 2012). The heartwood percentage was found to be significantly varied between provenances at the base of the tree height, but higher up in stem, the variation reduced and was found to be non-significant. Such failure to detect difference may possibly be because of large variation within provenances (Fries, 1999). Highest heartwood found at the base of the stem were from the provenances of Kerala seed source (81%), Oriomo (78%) and Pascoe River (73%) provenances.

From the results it can be presumed that substantial portion of the total stem wood was occupied by heartwood for *A. mangium* in the present study. This is an important aspect for the potential timber utilization of the wood, because heartwood is considered as one of the most important tree properties to establish the timber value of the stems (Harrison, 1974), but this has to be taken with caution, especially for young and fast growing trees species (Farrell *et al.*, 2009). Besides, *A. mangium* face one critical drawback, though a sizable proportion of the stem wood is occupied by the heartwood. The presence of soft inner core wood is one of the deterrent characters for used as solid wood materials, because it detached easily from the wood while drying. The soft core wood was estimated to occupy around 7 percent to 14 percent of the wood volume (Dhamodaran and Chacko, 1999). So, further improvement program should also focus on reduction of soft inner core wood of the species.

The result of study on two Swedish provenance test series of *Pinus sylvestris* indicated that stand characteristics such as stand density had stronger influence than provenance on heartwood and sapwood properties (Fries, 1999). The differences due to provenance origin were found to be very low in the study. However, in the present finding, large proportion of the total variation at the basal (81%) and middle portion of the stem (56%) were substantially under the genetic control, although at top portion of the stem the genetic control scale down to a very low proportion of 5 percent. Similarly, in *Pinus sylvestris* high narrow sense heritability (54%) was found to be associated with heartwood (Ericsson and Fries, 1999). Heritability of sapwood/heartwood ratio was also found to be moderate (39%) for *E. grandis* (Santos *et al.*, 2004). Therefore, there is good scope for improving the sapwood-heartwood content of the provenances through selection of the provenances. For harvesting, it is important to take into account the age and diameter size. Harvesting at early age will yield more sapwood content because of the positive correlation between diameter and heartwood content (Semple *et al*., 1999; Knapic *et al.*, 2006).

5.3.2 Basic density

Basic density is an important wood property and it is closely related to the raw material quality for pulping and suitability of wood for other types of processing (Watt *et al.*, 2008). Wood density correspond to higher pulp yields on a raw material volume basis and to a better use of digestor capacity as well as high wood density combined with high volume growth maximizes production on the unit area basis (Miranda *et al.*, 2001; Wimmer *et al.*, 2002).

The average basic density estimated for the provenances, irrespective of the height level, was 492 kg m^{-3}. It was higher than *Eucalyptus dunii* (466 kg m^{-3}), which can give higher yields of pulp and superior paper making properties than the widely accepted *E. grandis* for its pulping quality (Arnold *et al.*, 2004). The present finding is comparable with the average basic density (508 kg m^{-3}) estimated at different height levels for 10 years old *A. mangium,* grown in other parts of the state (Dhamodaran and Chacko, 1999) and the density (467 to 675 kg m^{-3}) estimated for the 14 years old species grown in Malaysia (Lim and Gan, 2000). However, it is lower than the average basic density of five mature trees (544 to 741 kg m^{-3}) of almost all the eleven species studied by Bhat *et al.* (1985), which are locally available in Kerala. It is higher than only two species *viz. Anacardium occidentale* (437 kg m^{-3}) and *Erythrina stricta* (233 kg m^{-3}), out of the eleven.

Channeling most of the resources to height development and compromising its strength at the early stage of growth to avoid competition was noted as one of the reason for reduction in density and strength of juvenile wood and the earlier part of the heartwood as it move along the height of the tree (Lokmal and Mohd Noor, 2010). However, this does not seem to explain the present finding of density that increased with height.

In the present study, the average basic density of the entire provenances decreased as it moves upward from the base (477 kg m^{-3}) to middle portion (468 kg m^{-3}) of the tree height and again increased to 530 kg m^{-3} at the top portion of the tree. In the study of Lim and Gan (2000), similar pattern of variation for basic density was observed in most cases. The density was found to decrease from base until it reached the middle portion before increasing towards the top of the tree. Significant differences between the provenances were observed at all the height level in the present study. At the base of the tree height, Kerala seed source (533 kg m^{-3}) had the highest basic density and differed significantly from Balimo (397 kg m^{-3}) and Pascoe River (444 kg m^{-3}) provenances, while the remaining provenances were on par with the local seed source. Provenance of Upper Aramia (488 kg m^{-3}) was found to be the highest at the middle portion and lowest was from Balimo (421.44 kg m^{-3}). At the top portion of tree height, the provenances that had the highest density was from Arufi Village (600 kg m^{-3}) followed by Tully-Mission Beach (585 kg m^{-3}). These two provenances differed significantly from Oriomo (452 kg m^{-3}), Claudie River (467 kg m^{-3}) and Balimo (471 kg m^{-3}), but the rest of the provenances were on par with the two provenances at the height level. Change in density along the longitudinal axis varied among provenances (Table 27). It followed three patterns of variation. The provenances of Tully-Mission Beach, Kuranda, Pascoe River, Lake Murray, Binaturi and the Kerala seed source exhibit the first pattern variation that showed a decreased in basic density as it moved from base to middle portion of the stem and again increased as it moved to top portion (Figure 8A). In this pattern of variation, highest density was observed at the top portion of the tree height level. The second pattern of variation of density showed a continued rise in the density from base to top. So, highest density was again at the top portion of the tree stem (Figure 8B). The provenances that followed this pattern were Arufi Village, Balimo and Upper Aramia provenances. On the contrary, Claudie River and Oriomo provenances, which followed the third pattern of variation, exhibited the highest density at the middle portion of the stem height level and decreased as it moved downward and upward direction of the tree stem axis (Figure 8C). Understanding such pattern of density variation is necessary for tree breeding program. It is laborious and difficult to estimate the accurate density based on volume and dry weight following the destructive sampling when large numbers of trees are to be surveyed. Consequently, a penetrometer called pilodyn had been employed to provide easy and quick information. The application of the instrument had been found to be fairly genetically correlated with the actual density (Kien *et al.,* 2008; Chen *et al.,* 2015), but such method failed to consider the variation present within the tree and substantial deviation will observed if it failed to take into account the variation. So, understanding the variation within the tree is an important step to predict and provide more reliable information of density of a provenance.

In general, the Kerala seed source (531 kg m^{-3}) had the highest average basic density followed by Kuranda (521 kg m^{-3}) of Queensland and Arufi Village (519 kg m^{-3}), Binaturi (512 kg m^{-3}) and Upper Aramia (508 kg m^{-3}) of Papua New Guinea and lowest was from Balimo provenance (430 kg m^{-3}), followed by Oriomo provenance (463 kg m^{-3}) of Papua New Guinea. Similar finding of better performance by the local seed source had also been reported in *Guazuma crinite* (Weber and Montes, 2007). In a provenance trial of *A. mangium* in Malaysia, it was also found that the provenances of Queensland had the highest (0.570) as well as the lowest (0.562) specific gravity (Lokmal and Mohd Noor, 2010).

The result showed that the contribution of genetic effect to the total variation of basic density of all the provenances was moderate at lower portion and high as it moved towards the top portion of the stem (Table 28). Consequently, genetic gain was high at the top portion and moderate at the lower two portions of the stem. Therefore, further improvement through selection can be made for the provenances. There was not much difference between the GCV and ECV for the trait in the present trial. The heritability estimated in the present study was higher than the heritability of growth parameters. This is in line with the reports of other researchers like Zobel *et al.* (1983) and Arnold *et. al.* (2004). Moderate heritability (42%) had also been reported in *Eucalyptus* species (Arnold *et al.*, 2004) as well as low heritability (18%) in *A. auriculiformis* (Susanto *et al.,* 2008). Heritability of wood can be varied with differences in site (Arnold *et al.,* 2004) as well as can be influenced by the variation in wood density components, especially the latewood density, at least for conifer species (Louzada and Fonseca, 2002). But, in general, wood density has high heritability and responsed well to an improvement program (Zhang *et al.,* 2003; Stener and Hedenberg, 2003). The present finding of high genetic influence on basic density support the findings.

Acacia species is classified as a light hardwood with a density of 420 to 483 kg m^{-3} (Abdul-Kader and Sahri, 1993). It compared favorably with eucalyptus wood in pulp and paper quality, but its wood often falls below the ideal density range (500 to 600 kg m^{-3}) for bleaching grade hardwood pulps for fine papers (Semple *et al*., 1999). Hence, it has been suggested that the species needs to be preferentially selected for higher density to improve its pulping characteristics (Balodis and Clark, 1998). The present finding highlights the variations and potential for further improvement of the species using the provenances for *A. mangium* in Kerala. However, these needs to be taken with caution when the objective is to improve volume and dry matter, as there are findings that support the negative correlation between growth and density (Walker and Woollons, 1998; Stener and Hedenberg, 2003; Zhang *et al.*, 2004; Deng *et al.,* 2014), but such negative correlation (-0.092 to 0.115) were found to be weak in the present study (Table 31). Moreover, Semple *et al.* (1999) suggested wood density should not be used as the sole criterion for assessing the suitability of tropical *Acacias* for pulp and paper manufacture as it did not correspond well with the ease of bleaching and brightness required. Nonetheless, the present study showed that the Kerala seed source, Kuranda provenance of Queensland and Tully-Mission Beach, Arufi Village, Upper Aramia and Binaturi provenances of Papua New Guinea will be the best provenances to choose for further improvement program, if selection were to be followed based on wood density. The four provenances and local seed source were within the ideal density range for pulp and paper making.

5.3.3 Fiber morphology

Acacia mangium has become one of the world's major plantation species for pulpwood production (Griffin *et al.,* 2014). It is primarily used for pulp and paper in south East Asia. It can be bleached to high brightness and makes excellent writing paper. Despite being an important source for pulpwood production, it is difficult to get information regarding the variation in fiber morphology between provenances of the species. This necessitates the study for variation in fiber morphology between provenances for the species.

The fiber of *A. mangium* is short (Shari *et al.,* 1993). The average fiber length, fiber diameter, lumen width and fiber wall thickness estimated for the entire provenances in the current study was 977.55 µm, 25.30 µm, 21.69 µm and 3.61 µm, respectively. It was higher than the estimated mean fiber length (954 µm), fiber diameter (20.3 µm) and lumen (11.2 µm) of 16 years old *A. mangium* grown in Malaysia, but lower than the mean fiber wall thickness (9.2 µm) reported by Lim and Gan (2011). Yahya *et al.* (2010) reported a slightly higher mean fiber length of 982 µm, but lower fiber diameter (19.39), lumen width (14.29) and wall thickness (2.55). Still higher fiber length of 1017 µm and wall thickness of 4.3 µm had also been reported from Malaysia (Sahri *et al.,* 1993). The present finding of fiber length was lower than average fiber length estimated for nine years old *Eucalyptus grandis* (1150 µm) grown in Kerala (Bhat *et al.,* 1990). It was also lower than the fiber length (1068 and 1194 µm) estimated for *Acacia* hybrid (Yahya *et al.,* 2010; Chong *et al.,* 2013).

Provenances formed a significant source of variation for fiber morphology in the present study. Provenances from Queensland were found to be among the highest as well as the lowest fiber length (Table 29). Kuranda provenance of Queensland had the highest fiber length (1091 µm) and Pascoe River was among the provenances having the shortest fiber length (911 µm). The variations among the provenances of Papua New Guinea were less noticeable, because the provenances from the region had more or less similar fiber length.

For fiber diameter, Queensland provenances tend to have lower diameter than Papua New Guinea. Balimo provenances (28 µm) had the highest fiber diameter in the present study, followed by Binaturi (27.62 µm) and Oriomo (24.48 µm) provenances of Papua New Guinea. Highest lumen width was recorded from Binaturi provenance (24.05 µm) and Balimo provenance (24.42 µm) of Papua New Guinea, while the rest of the provenances were more or less the same. In case of wall thickness of fiber, five provenances *viz* Tully-Mission Beach, Arufi Village, Balimo Upper Aramia and Binaturi provenances, had the thickest wall that ranged from 3.53 to 3.95 µm. The local seed source was found to be among the least value obtained for all the aforementioned fiber characteristics.

Fiber morphology is a major determinant of paper properties (Griffin *et al.*, 2014). Fiber length positively influence the pulp yield, tear index, bending stiffness and permeance of pulp and handsheet properties and negatively influence alkali consumption (Wimmer *et al.*, 2002; Jahan *et al.*, 2010). In combination with wood density and microfibril angle, fiber length was able to explain 52 percent of the pulp yield variance, 45 percent of the active alkali consumption variance, 72 percent of the total variance of tear index at zero beating and over 50 percent of bulk density, tear, tensile and burst indices after beating in *Eucalyptus golobulus* (Wimmer *et al.*, 2002). Fiber wall thickness is an important factor in controlling the hygroexpansivity of paper through fiber network activation (Pulkkinen *et al.*, 2009). The study found that in hardwood species including *A. mangium,* thin walled fibers with homogeneous wall thickness distribution shrinks less during drying and swells less during rewetting than a fiber network consisting of thick-walled fibers with heterogeneous wall thickness distribution over a relative humidity range from 10 percent to 90 percent. Fiber wall thickness was also found to be an important factor for pulp yield, sheet density, Kappa number, etc. for *E. camaldulensis* (Ona *et al.,* 2001).

Nevertheless, it is not possible to fully categorize the performance of the pulp based on a single morphological factor (Horn, 1974; Oluwadare *et al.*, 2007) and the influence of fiber length and wall thickness on the strength properties is most pronounced in the unbeaten pulp. After beating, different indices like runkel ratio, rigidity, flexibility and slenderness play a greater role (Oluwadare *et al.,* 2007). The indices are derived values, so they reflect the variations in the fiber characters that vary depending upon species, sites and provenances.

The present study showed that the influence of the provenance on slenderness of *A. mangium* was significant, but no significant influence on the runkel ratio, rigidity and flexibility coefficients were observed. Provenances from Queensland and Papua New Guinea showed almost similar variation in slenderness (Table 29). Besides the local seed source, provenances from both the regions were among the highest slenderness *viz.* Kuranda provenances (47.06) of Queensland and Lake Murray (43.79) and Upper Aramia (43.06) provenances of Papua New Guinea. Lowest mean of the ratio with no significant difference was also observed in both the regions. Claudie River (39.29) provenances of Queensland and Binaturi (36.06), Oriomo (36.23), Pascoe River (40.58) and Balimo (33.76) provenances of Papua New Guinea were among the least. Because of the association of slenderness with high heritability, GCV and genetic gain, selection should be done on the best five provenances mentioned above.

High slenderness ratio is expected to give low degree of collapsing and conformability which in turn defines the tearing strength, porosity, bulk and opacity of paper (Dutt *et al.*, 2004). In one of the study, mean slenderness ratio of seven year old *A. mangium* was estimated to be 51.29 (Yahya *et al.*, 2010), much higher than the highest estimated ratio from Kuranda provenances of the present study. In the study of Yahya *et al.* (2010), slenderness of *A. mangium* was found to be on par with *A. auriculiformis* (52.65) but lower than *Acacia* hybrid (57.4). Dutt and Tyagi (2011) also reported the slenderness ratio of eleven *Eucalyptus* species to be in the range of 25.28 to 55.18. The slenderness ratios estimated in the present study as well as in the other studies as mentioned were low. The criteria based on slenderness ratio to qualify fibrous materials as worthwhile for quality pulp and paper production is 70 (Young, 1981; Bektas *et al*., 1999**)** and in conformation with the criteria some studies had found that the important pulp producing species like *E. tereticornis* and Bamboo had the ratio above the specified range (Dutt *et al.,* 2004**;** Sreevani and Rao, 2013). However, Ates *et al.* (2008) contested that the property that depends on slenderness ratio is also influenced by the cell wall thickness and slenderness ratio is not the only decisive factor to decide the property.

Runkel ratio is considered as the best fiber dimension ratio (Barefoot *et al***.**, 1964; Kibblewhite, 1982). Ogunjobi *et al.* (2014) classified species as highly pulpable if runkel ratio falls below 1.0. The overall mean runkel ratio of the provenances used in the current trial had 0.35. The provenances did not differ significantly from each other. Such low ratio is favorably related with paper conformability, pulp yield and mechanical strength properties of paper (Ogbonnaya *et al.,* 1997; Dutt and Tyagi, 2011). The estimated runkel ratio was on par with the reports of Yahya *et al.* (2010). In the report it was estimated that the seven year old *A. mangium* had 0.37 runkel ratio, while *A. auriculiformis* was found to possess much higher ratio of 0.55. Fourteen years old *E. camaldulensis* (0.36 and 0.48) and *E. globulus* (0.36 and 0.42) were also found to possess higher ratio than the present finding (Ona *et al.,* 2001). Similarly, many findings of higher runkel ratio (0.40 to 1.88) had been reported for other *Eucalyptus* species (Dutt and Tyagi, 2011: Sharma *et al.,* 2011; Ibrahim and Abdelgadir, 2015). Besides being categorized under favorable runkel ratio, the provenances had moderate heritability (32%) for the trait. This provide an advantage for further breeding program using the provenances. Selection based on the superior individual can be followed as provenance variations were low. However, the traits were found to be highly influenced by environment (Table 29), so depending upon the environmental condition that prevails in the site, the ratio may vary.

Rigidity coefficient measures the physical resistance properties of paper. High rigidity ratio gives lower paper strength properties and so the lower tensile, tear and burst indices (Bektas *et al.,* 1999). Therefore, for pulp and paper production it is desirable to have low rigidity coefficient. In the present study, the provenances did not show significant differences in the coefficient. The overall mean rigidity coefficient estimated for the entire provenances of *A. mangium* in the study was 29.21. The average ranged from 27.03 to 31.37. It is higher than the coefficient (13) reported for the species grown in Indonesia by Yahya *et al.* (2010) and Yahya (2012) and also to the coefficient of *Acacia* hybrid (12) reported by Chong *et al.* (2013). However, the lower value estimated in their study is due to the differences in formula used for calculating the rigidity coefficient. They had calculated the coefficient using only one cell wall thickness of a fiber, rather than double cell wall thickness as given by Dutt and Tyagi (2011). If double cell wall thickness were used in their study, the rigidity coefficient for the studies will be 26 for *A. mangium* and 24 for *Acacia* hybrid, which will be comparable with the present study. The present finding was also comparable with the rigidity coefficient of *E. grandis* (28), which is widely accepted for pulping, reported by Dutt and Tyagi (2011). This indicates that the provenances of *A. mangium* used in the current trial had rigidity coefficient within the limit for considering as favorable for pulp and paper production. Moreover, the rigidity coefficient of the provenances in the present study was moderately heritable (45.06%). Genetic gain (24.06%) estimated at 5 percent selection intensity was also found to be moderate. Therefore, even though the variation within the provenance is low, it provides an ample scope for selection for further breeding program.

Coefficient of flexibility is also an important factor that affects the pulp and paper properties. Fibers with high coefficient of flexibility are flexible, collapse readily and produce good surface contact and fiber-to-fiber bonding, as well as increase the paper strength (Ogbonnaya *et al.*, 1997). Therefore, high coefficient of flexibility (preferably >60) is necessary for fibers to be used in paper-making (Okereke, 1962). The present finding showed that all the provenances of *A. mangium* had flexibility coefficient more than 80, with an average of 85.42. Fibers possessing such high coefficient were categorized under highly elastic fibers (Anoop *et al.*, 2014). So, the estimated coefficient of the provenances is high enough to be considered for use in paper-making. Flexibility coefficient of the provenances was at the higher end when compare with the same species grown in Indonesia (Yahya *et al.*, 2010; Yahya, 2012). The estimated mean of flexibility coefficient in their study was 73 and 74. It was also higher than the estimated mean (75) of *Acacia* hybrid (Chong *et al.*, 2013). Further advantage for selection using the provenances is that the index has moderate heritability (41.43%).

The present finding showed that the indices that are considered important for pulp and paper production for the provenances are within the accepted limit and comparable with some of the important species used for commercial pulp and paper production. Coupled to its potential for pulp and paper production, the basic density was found to be strongly and positively correlated with fiber length (0.412) and negatively with fiber diameter (-0.374; Table 31). Increase in fiber length positively affects the slenderness ratio and decrease in fiber diameter also positively affects the slenderness ratio, rigidity coefficient and flexibility coefficient. Correspondingly, slenderness ratio, which is influenced by both the fiber characters, was found to be significantly correlated (0.472) with density in the present study. This indicates that selection of density for further improvement will also favor the improvement of fiber indices *viz.* slenderness ratio, rigidity coefficient and flexibility coefficient. Therefore, it will reduce the time and money for improving the pulping properties of the provenances through selection based on a single property i.e. density. However, it is also important to note that density has significant and negative correlation with lumen width (-0.350). Lumen width is related with the runkel ratio and flexibility coefficient. Decrease in the lumen width will increase the runkel ratio and reduce the flexibility coefficient, which is not a desirable outcome for pulp and paper production. But, in the present case there was no significant correlation with runkel ratio and flexibility coefficient. Therefore, it can be concluded that for improving the pulping properties of the provenances, density can be used as the selection criteria. Based on the finding, the Kerala seed source, Kuranda, Upper Aramia, and Binaturi provenances can be recommended for further improvement program for pulp and paper production because of their high basic density and favorable fiber morphology. Moreover, fiber properties were found to be substantially under the genetic control. The GCV was also found to be higher than ECV and the genetic gain were found to be high for most of the traits. Suitability of *A. mangium* grown in Kerala condition for use in paper and pulp production had been confirmed by Anoop *et al.* (2012) based on anatomical properties. After studying the extractives present in the wood of *A. mangium* grown in Malaysia and comparing with the findings reported from Phillipines and Indoensia, Koh (2011) also concluded that the species is an acceptable source of raw material for the pulp and paper industry.

5.3.4 Mechanical properties of wood

Mechanical property of wood was investigated only for five randomly selected provenances *viz.* Arufi Village, Claudie River, Kuranda, Upper Aramia and Kerala.

Mechanical properties tested for the provenances were static bending *viz.* Modulus of rupture (MOR) and Modulus of elasticity (MOE), and maximum compressive stress parallel to grain (MCS). The test was conducted in partially air-dry wood, because the average moisture content of wood at test in the present study was 24 percent. It was much higher than the normal standard moisture content of 12 percent for air-dry wood.

In the present study, the mechanical properties of wood estimated for the provenances did not differ significantly between the provenances. Shanavas and Kumar (2006) reported lower mechanical properties of wood for the species compared to the value estimated in the present study. The MOR and MOE for static bending and MCS for compression parallel to grian estimated in their study were 570.6 kg cm^{-2}, 80234 kg cm^{-2} and 323.2 kg cm^{-2}, respectively. But, the present finding is comparable with the studies reported from other countries. The average MOR, MOE and MCS reported from Malaysia was 810.67 kg cm^{-2}, 105510.0 kg cm^{-2} and 469.1 kg cm^{-2} respectively for 16 years old *A. mangium* (Omar and Jamil, 2011). Peh and Khoo (1984) also report from Malaysia an average mean of 595.5 kg cm^{-2}, 119011.1 kg cm^{-2} and 443.6 kg cm^{-2} for MOR, MOE and MCS respectively.

Static bending strength of the provenances were comparable with some of the durable and important species like *Tectona grandis*, *Dipterocarpus bourdilloni*, *Dalbergia latifolia*, *Gmelina arborea*, etc. found in Kerala, but the MCS was relatively low even when compared with moderately durable species like *Grewia tilifolia* (701.2 kg cm^{-2}), *Albizia procera* (570.1 kg cm^{-2}), etc. and perishable species like *Dillenia pentagyna* (514.6 kg cm^{-2}), *Canarium strictum* (548.2 kg cm^{-2}), etc. (Nazma *et al.*, 1981). High moisture content at test could be one of the contributing factors for lower values of mechanical properties.

Genetic control seems to play a greater role for the properties investigated in the current study. Static bending strengths were found to be moderately heritable, while heritability of compression parallel to grain was high (Table 33). The expected genetic gain at 5 percent selection intensity was also moderate to high for mechanical properties. This will have a positive bearing in improvement programmes. Similar finding in *E. grandis* had been reported by Santos *et al.* (2004). The study showed moderate heritability for static bending (50%) as well as for compression parallel to grain (57%), but genetic gain at 20 percent selection intensity in their study was found to be low for the two properties, 4.40 percent and 6.25 percent, respectively. In the present study, ECV was found to be higher than the GCV for MOR, but lower than GCV for MOE and MCS.

The results showed that the five provenances fared well in mechanical strength as many other common species found in Kerala and it has the potential for further improvement in the provenances through selection, because of the strong genetic influence on the traits. But, for specific end use, mainly as solid wood purpose, the species may not be as favorable as expected because of the presence of soft core wood (Dhamodaran and Chacko, 1999). Further studies and improvement programmes need to be done to address these issues, if the species are to be considered for diversified uses.

5.3.5 Conclusion

The importance for screening and selection of superior provenances of fast growing and important exotic species like *A. mangium* in the Kerala state is reiterated by the increasing demand for used as timber and narrow genetic base associated with the species. The present study evaluates the variation of ten provenances and one local seed source of *A. mangium* to facilitate selection of superior and suitable provenances of the species in the state as well as to provide a basis for further improvement program.

In the present study, there were substantial variation in morphometric traits of seed, seedling height, tree height and wood properties of the provenances of *A. mangium.* It also highlights the importance of collection of large sized seeds, because of its strong correlation with seedling height. However, the site condition seems to be apparently poor and this might have impacted the growth potential and other related properties of the provenance. Therefore, the provenances failed to exhibit their potential to the fullest.

Study of the basic information regarding the genetic patterns also revealed that almost all the desirable characters studied were under moderate to strong genetic control. But most importantly, the finding showed that genetic control over height at young as well as mature stage was higher than girth. Therefore, more emphasis must be given to selection based on height for the provenances of *A. mangium* for higher genetic gain. It is also important to note that the heritability estimated in the present study was broad sense heritability, which is important only if both the additive and non-additive variation can be transferred from parent to offspring (Zobel and Talbert, 1984) as in vegetative propagations or specific crosses between parents. Otherwise, it has limited applicability. Substantial differences in the narrow and broad sense heritability can exist for the same observation. For instance, Toda *et al.* (1958) obtained high broad sense heritability of 68 percent for specific gravity in *Cryptomeria* species, while for the same observation narrow sense heritability was found to be just 27 percent. Therefore, the values of genetic parameters estimated in the studies should be considered with caution.

The finding of the performances of the provenances and its genetic parameters highlights the need to recognize the variation that are associated with the provenances of *A. mangium* for specific end uses and its potential to use for further improvement program. The cluster analysis (Figure 9) showed that Kerala seed source, Kuranda and Tully-Mission provenances of Queensland and Arufi Village, Upper Aramia, Binaturi and Lake Murray provenances of Papua New Guinea are more closely related than other provenances. The provenances, except the Kerala seed source, Lake Murray and Tully-Mission Beach, also showed better performances in height compared to other provenances. They performed well in the seedling stage as well, except the Kerala seed source. Therefore, selection for improvement and recommendation for production program must be made on the seven provenances. They also have good potential for pulp and paper production, because of their favorable density and fiber morphology. But the provenances of Balimo, Claudie River, Pascoe River and Oriomo may not perform well in the state because of their poor performances in most of the characters observed in the present study.

There is an urgent need to increase the wood quality of *A. mangium*, because of the increasing interest in using the species for the production of solid-wood products and to fully utilize its potential for diversified end uses. This can be achieved by reducing the presence of soft core wood and the incidences of heart-rot and root-rot infection through resistance breeding program. The test for mechanical properties also indicated that the provenances can be used for solid-wood products as any other common species used for the purpose. So, further studies should focus on reducing the aforementioned defects which are very common and major threat to the sustainability of pulp and solid-wood industries based on tropical *Acacias*, in particular *A. mangium.*

SUMMARY

6. SUMMARY

The present study on provenance evaluation of *A. mangium* for growth and wood traits was conducted at the Livestock Research Station, Thiruvazhamkunnu. Variation in the performance of two to five month old progeny of the provenances were evaluated in the nursery located at the College of Forestry, Kerala Agricultural University. Salient findings of the study are summarized below.

1. Survival percentage of the provenances was found to be high (63% to 89%), but did not differ significantly between the provenances.

2. The variation in the height at 14th year was significantly different between the provenances. The provenances having the best performance in height were Kuranda (22.12 m), Arufi Village (21.36 m) and Upper Aramia (21.27 m). The differences between the provenances in DBH, volume, clear bole height, tree form and branching habit were not significant. All the provenances showed decrease in MAI from 5th years of growth. Oriomo provenances consistently outperformed other provenances.

3. Highest heritability in growth attributes was observed in height (63.30%), while the rest of the traits considered in growth attributes were low (25.98%) to moderate (49.39%). Height of the provenances also had higher GCV (15.29%) than ECV (11.64%), but in other growth traits ECV (1.72% to39.04%) was higher than GCV (1.55% to 38.57%).

4. Stability analysis showed that genotype×enviornment interaction was not significant. Kuranda and Arufi Village provenances had the highest stability among the provenances.

5. Morphometric traits of seeds were found to be significantly different between the provenances. Seed weight, width and thickness of Arufi Village were

found to be significantly higher than the other provenances. Tully-Mission Beach and Pascoe River provenances had the highest seed length.

6. Analysis of genetic parameters showed that morphometric traits of seeds were under higher genetic influence than environment and had high heritability (>90%).

7. Viability of the provenances was high (81.65%) and the study confirmed that *A. mangium* has physical dormancy.

8. Lake Murray provenance showed the best performance in germination related parameters, followed by Claudie River, Balimo and Binaturi provenances. Heristability ranged from moderate (55.84%) to high (80.67%) for the traits and GCV (6.45% to 25.06%) was higher than ECV (5.74% to 16.75%).

9. Variation in seedling height was found to be significantly different between provenances. Lake Murray, Kuranda, Pascoe River and Binaturi provenances performed the best throughout the study period. The provenances showed no significant variation in collar girth and RGR.

10. Heritability was moderate to high for five months old seedlings and GCV increased with age for the seedling growth attributes.

11. Seed weight (0.239 to 0.333) and seed width (0.314 to 0.335) had strong correlation with seedling height.

12. Heartwood percentage was found to be significantly different between provenances at the base of the tree height, while it did not differ at middle and top portion of tree stem. Oriomo (79.12%), Pascoe River (73.41%) and Kerala seed source (81.22%) had the highest heartwood percentage. Heartwood content tends to be under higher genetic control.

13. Basic density was found to be significantly different between provenances at the base, middle and top portion of the tree height. In general, the Kerala seed source, Kuranda, Arufi Vilage, Binaturi, Upper Aramia and Tully-Mission Beach provenances had higher density. Average basic density of the entire height level was above 500 kg m^{-3} for these provenances. The present study showed that density is strongly under genetic control (48.71% to 64.06%).

14. The differences between provenances in fiber length, fiber diameter, lumen width, wall thickness and slenderness ratio were found to be significant. But, the provenances did not differ significantly from each other in indices like runkel ratio, rigidity coefficient and flexibility coefficient. Provenances of Kuranda (47.06), Lake Murray (43.79), Upper Aramia (43.06) and Kerala seed source (46.23) had the highest slenderness ratio.

15. Heritability of fiber morphology was moderate (31.61%) to high (87.08%). Environmental coefficient of variation (3.27% to 22.05%) was higher than GCV (2.75% to 17.40%) for runkel ratio, rigidity coefficient and flexibility coefficient, but GCV (22.43% to 45.10%) was higher than ECV (10.28% to 16.19%) for the other traits of fiber.

16. Density was significantly and positively correlated with fiber length (0.412)) and slenderness (0.472), but negatively with fiber diameter (-0.374) and fiber wall thickness (-0.350)

17. Mechanical peoperties of wood of the five provenances were not significantly different. The average MOR, MOE and MCS estimated was 872.30 kg cm^{-2}, 123643.6 kg cm^{-2} and 386.30 kg cm^{-2}, respectively. It is comparable with some of the durable and important species commonly found in Kerala. No significant correlation was found between the properties and density, growth attributes and fiber morphology.

18. Kuranda and Tully-Mission Beach provenances of Queensland and Arufi Village, Upper Aramia, Binaturi and Lake Murray provenances of Papua New Guinea and Kerala seed source showed the best performance in most of the traits studied and can be recommended for growing in Kerala. The provenances have good potential for used as pulp and paper production.

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PROVENANCE EVALUATION OF *Acacia mangium* Willd. FOR GROWTH AND WOOD TRAITS

by

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ABSTRACT

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ABSTRACT

A provenance evaluation of *A. mangium* was conducted in 14 year old plantation at Livestock Research Station, Thiruvazhamkunnu, to understand the variation in growth and wood traits among the provenances. Ten provenances and one local seed source was used for the trial.

The provenances had high survival percentage (77.44%), but did not differ significantly between provenances. Significant differences between provenances were found in tree height, while they were on par for DBH, volume, tree form and branching habit. The provenances of Kuranda, Arufi Village, Upper Aramia, Oriomo, Balimo and Binaturi were taller than the rest. Heritability of growth attributes was highest for height (63%). Morphometric traits of seeds were found to be significantly different between the provenances. Arufi Village provenance was found to be better than the other provenances for the traits. Seed weight and seed width were found to be strongly correlated with seedling height. Variation in germination energy, germination value and germination period were also significantly different between provenances. Lake Murray provenances showed the best performance in most of the parameters studied for germination. No significant differences between provenances were observed for germination capacity. Germination parameters are under moderate to high genetic control. Significant differences were noticed among the progenies of the provenances in height, while they did not differ in terms of collar girth and RGR.

The provenances differed significantly in physical properties of wood, but not in mechanical properties. The provenances differed significantly for heartwood only at the base, while basic density was significantly different at all the height levels. Density was significantly and positively correlated with fiber length and slenderness, but negatively with fiber diameter and fiber wall thickness. The variations in fiber morphology between the provenances were also found to be significant. However,

runkel ratio, flexibility and rigidity coefficient did not differ significantly between the provenances. Wood properties of the provenances were under strong genetic control.

Based on the study, Tully-Mission Beach, Arufi Village, Kuranda, Upper Aramia, Lake Murray and Binaturi provenances can be recommended for growing under Kerala condition.