1. Introduction

As the global population grows and areas of native forest decrease, particularly in developing countries, tree plantations and agroforestry have become an increasingly important source of timber, fuelwood and raw materials for pulp and paper. Eucalypts are now being widely used throughout the world for wood, pulp and other tree products. Eucalypts are highly productive and well adapted to dry, infertile sites, and are important for degraded land that are no longer suitable for agriculture. They also contribute in protection of land and water systems. In Asia, particularly in India, China, Vietnam and Thailand, eucalypt plantations support major industries and contribute to alleviation of rural poverty.

Existing forests in India cannot meet national demand for firewood, timber and wood based products on sustainable basis because of low growing stock, poor increments, inadequate financial and technological inputs, unbearable biotic pressures and serious degradation of forest resources (Piare Lal, 2010). Per hectare growing stock in forests in India has been estimated at around 69 m³ ha⁻¹ for the year 2005. It is significantly below the global average of 110 m³. The productivity of Indian forests is low; i.e., 0.7 m³ ha⁻¹ against the world average of 2.1 m³ ha⁻¹. Even plantations raised provide less than their potential. India is world’s biggest consumer of fuel wood with 40 per cent of the population dependent on fuel wood for basic energy needs with a total demand in the range of 200-230 Mt. It is estimated that 100-115 Mt of fuel wood is extracted from natural forests, which is almost 6 to 7 times higher than the estimated sustainable supply of 17 Mt from the forests. This unsustainable exploitation leads to degradation of forests. Similarly, the requirement for timber was estimated at 54.94 Mt for 2006. On the supply side, an estimated 28.81 Mt is contributed by farm forestry, 9.38 Mt is harvested from forests and 2 Mt imported. That still leaves a gap of 14.74 Mt, much of this is exploited from forests. India is the fastest growing market for paper globally and the paper consumption is estimated to touch 13.95 Mt by 2015-16. Since the wood based industry in India is
mainly plantation based, it is essential that more land must be brought under productive plantations of trees species suitable for the making of paper for meeting the future requirements.

In the present scenario when the demand of wood and wood-based products is increasing day by day, interest is being concentrated on growing short rotation species to bridge the gap between the growing demand and inadequate supply of wood. Eucalypts provide major raw material for the pulp and paper industries in India, so it is imperative that planting stock of high genetic quality be used to increase the yield from plantations (Varghese et al., 2008). The pulpwood shortage in India created the need for quick growing species. The biggest single urge to plant eucalypts in large scale plantations was provided by the demand for wood fibre for the paper industry (Shiva et al., 1981). Achievements in genetic yield improvement of forest tree species have been less spectacular than that in agricultural crops because the forest tree species are more difficult to breed than agricultural crops and due to their long generation times, prevalence of out breeding and the operational difficulties. These problems have restricted the large scale, commercial breeding of eucalypts and other forest tree species to random mating of selected trees on very limited experimental scale only as in seed orchards. There is a scarcity of information on realized gains from eucalypt improvement programmes in the country.

2. Historical Background
The eucalypt tree originally came from Tasmania (Australia) and other Indo-Malaysian islands. There are approximately 700 species of eucalypt, all with great environmental value; 37 of these species are of interest for the forest industry while only 15 are used for commercial purpose. Eucalyptus deglupta and E. urophylla are the only two species not occurring in Australia. Eucalypt was first planted in India around 1790 by Tipu Sultan, the ruler of Mysore, in his palace garden on Nandi hills near Bangalore. According to one version he received seed from Australia and introduced about 16 species (Shyam Sundar, 1984). The next significant introduction of Eucalyptus was in the Nilgiri hills, Tamil Nadu, in 1843, and later (1856) regular plantations of E. globulus were raised to meet the demands for firewood (Wilson, 1973). E. tereticornis and a form of E. tereticornis known as Mysore gum (thought to be a hybrid) are the most widely planted eucalypts in India. This Eucalyptus hybrid represents about half of the eucalypts planted in many parts of India (Jacobs, 1981), and is believed to be derived from one small stand of E. tereticornis the early introductions in Nandi hills (Pryor, 1966; Chaturvedi, 1976). Lack of sufficient genetic variability (Ginwal et al., 2004 a, b) is one of the important reasons for low productivity of eucalypt plantations in India as compared to other countries because this restricts
the intensity of selection in insufficient base population. There are several reasons for raising eucalypts under large scale plantations in India; some are common and some are specific to the region. The most important common reason is production of wood for fuel, poles, construction and pulp.

The early introduction of *E. camaldulensis* and *E. tereticornis* to India were from southern temperate localities in Australia rather than the northern tropical regions where the climatic conditions closely resemble the areas available in India because of the inaccessibility and difficulties in collecting seeds (Boland, 1981).

3. Eucalypt Improvement in India

The natural forests of the country are under pressure of depletion largely on account of firewood needs of the ever-growing population. If the gap between demand and supply of firewood is not made up, it will further result in loss of natural tree cover. There is a need to plant fast growing species to bridge the gap. Eucalypts had played a great role in past to rescue the situation. However, the productivity of eucalypts is very poor in India, which is only about 10 to 15 m³ ha⁻¹ yr⁻¹ (Chaturvedi, 1973; Venkatesan *et al.*, 1986). Consistent tree improvement efforts are, therefore, required to address this challenge.

Considerable efforts have been made in domestication and improvement of eucalypts in India. A systematic genetic improvement programme for *Eucalyptus* in India was coordinated by Forest Research Institute, Dehradun (FRI) and Institute of Forest Genetics and Tree Breeding, Coimbatore (IFGTB). However, few pulp and paper companies particularly ITC Ltd. initiated a pioneering work in tree improvement of eucalypts and commercial deployment of the productive clones. Besides many state forest departments joined their hands in evaluation of the eucalypt germplam and clonal testing in the country. The overall objective of the tree-improvement programme was to identify species and/or provenances or the genotypes worth planting. The following are the major areas where tree improvement initiatives on *Eucalyptus* have been taken up with success:

- Introduction of species and their provenances
- Evaluation and identification of adaptable and productive provenances of successful species
- Identification/selection of superior phenotypes
- Clonal reproduction/propagation, testing and selection
- Establishment of seed orchards and production of quality seeds
- Development of hybrids through controlled crossing and their evaluation
- Establishing breeding populations

4. Eucalypt Breeding System

The genus *Eucalyptus* belongs to family *Myrtaceae* and comprises about 700 species/varieties (Eldridge *et al.*, 1994). The somatic chromosome number in eucalypt is 2n =
It is a cross-pollinated species resulting in wide variation and heterozygosity in the population. However, the reproductive system of eucalypt offers ample opportunity for self-pollination (Eldridge et al., 1994).

Eucalypt species normally develop chasmogamous flowers that are available for outcrossing and very rarely cleistogamous flowers that are obligately self-fertilized (Venkatesh, 1971; Venkatesh et al., 1973; Eldridge et al., 1994; Sharma et al., 2005). Chasmogamous flowers open and expose the stamens and styles to the environment. This allows the flowers to cross-pollinate with another individual. However, in cleistogamous flowers, the opercula show an unusual tardiness in shedding. They separate from the floral receptacle as usual, but do not shed and remain sitting on the styles even after withering and fruit formation. Selfing or outcrossing of a species is both genetically and environmentally controlled (Fryxell, 1957). The effects of selfing (other than cleistogamy) in eucalypts have been reported. These include reduced seed set (Pryor, 1976; Griffin et al., 1987; Potts and Sava, 1988; Tibbits, 1989), decreased germination per cent (Eldridge, 1978; Eldridge and Griffin, 1983), increased frequency of abnormal phenotypes (Hodgson, 1976; Potts et al., 1987), depressed field growth and vigour (Eldridge and Griffin, 1983; Potts et al., 1987; Griffin and Cotterill, 1988) and decreased nursery and field survival (Eldridge and Griffin, 1983; Potts et al., 1987). However, there are only a few reports, which indicate evidence of natural selfing due to cleistogamy in eucalypts (Venkatesh, 1971; Venkatesh et al., 1973). These reports are based on the observations recorded on a single standing tree, that too only at seed and capsule setting stage, and reflect less seed and capsule setting in the cleistogamous flowers than chasmogamous flowers.

In the year 2002 a provenance cum progeny trial of *E. tereticornis* comprising 13 provenances and 91 families of Australian and Papua New Guinea (PNG) origin was established in the campus of FRI. Out of 91 families, one family (DS 000141) emanating from the CSIRO seed lot no. 13418 was spotted with cleistogamous flowers, while the other adjoining trees of different seed sources growing at the same site showed normal chasmogamous flowers (Sharma et al., 2005). This preliminary observation was made at an early age of 18 months when few trees of this family showed flowering. The effect of forced selfing, was examined in this family after 48 months of field planting (Ginwal, 2010). Severely depressed seed set, germination per cent, field growth and survival in relative comparison to other outcrossing families were noticed. Inbreeding depression were noticed in growth traits, viz., height, clean stem height, DBH, branching and survival per cent, which increased with age.

The apparent presence of such forced self-families, in open-pollinated families has several implications for the management of tree improvement programmes. If seeds from open-pollinated seed orchards are used to establish new plantations, potentially achievable rates of gain may be compromised (Hardner and Potts, 1987).
1995). The management of breeding populations has tended to avoid inbreeding because of its deleterious effects. The results revealed that cleistogamy in *E. tereticornis* causes severe reduction in growth and survival in plantations and may lead to severe loss in productivity of wood. Hence a cautious approach may be adopted while making selections for tree improvement and collection of seeds for plantation programmes.

### 5. Species and Provenance Testing

Species and provenance testing is a means to exploit effectively the existing natural variation for tree improvement programmes. Considerable species and provenance trials were conducted between 1979 and 1983 with 58 species of eucalypts (Chaturvedi *et al.*, 1989). The initial results revealed that provenances of only two species, *E. camaldulensis* and *E. tereticornis*, performed well under rainfed conditions on the plains of India, so later trials concentrated on 32 provenances of the former species and 14 of the latter, tested at various locations. Several provenances of both test species performed better in height and diameter growth but none performed consistently well in all experiments. Furthermore, none were resistant to the heavy fungal attack on *E. camaldulensis* (principally by *Botryodiplodia* spp., *Corticium salmonicolor* and *Cylindrocladium* spp.) which occurs in the region.

Similarly, some 170 species of eucalypts and provenances of few species were tried in India (Bhatia, 1984), out of which the most outstanding and favoured has been the *E. tereticornis* and a form of *E. tereticornis* called *Eucalyptus* hybrid, popularly known as Mysore gum (Kushalappa, 1985). Other species which were grown on plantation scale were *E. camaldulensis*, *E. citriodora*, *E. globulus* and *E. grandis* during this period.

Even though eucalypts are grown extensively in Tamil Nadu, research on identification of provenance was not initiated until 1982. In that year, 15 provenances of *E. camaldulensis* and 14 of *E. tereticornis* of Australian origin were evaluated at Pudukottai, a predominantly eucalypt growing district in Tamil Nadu, as part of an IUFRO trial (Kumaravelu, 1995). Three provenances of *E. tereticornis* (Laura River, seed lot no. 10975 and 11953; Mt Garbine, seed lot no.13013 and Kennedy River seed lot no. 12947) and five of *E. camaldulensis* (Katherine, seed lot no. 12181; Richmond, seed lot no. 13008; Gibu River, seed lot no.12346; Gilbert River, seed lot no. 12963 and 12986) were found promising. Provenances of *E. cloeziana* were evaluated for five years in a high rainfall zone (2,000 mm to 3,500 mm) of Western Ghats (Manaturagimath *et al.*, 1991). The North-West of Cardwell QLD, provenance, showed the best performance in height, DBH and volume followed by South East of Gympie QLD.

Most eucalypt plantations across India are of Mysore gum, a land race considered to be a mixture of pure *E. tereticornis* and genetic segregates of interspecific hybrids,
displaying high variability (Kaikini, 1961). The growth of Mysore gum is quite slow, with mean annual increment of plantations averaging around 7 m³ ha⁻¹ (Chandra et al., 1992), and a number of trials have demonstrated superior performance of certain new eucalypt introductions (Varghese et al., 2001, 2008) or selected eucalypt clones (Piare Lal, 1993).

Pulp and paper company ITC Ltd. initiated a pioneering work in commercial deployment of the productive clones for the pulp wood production. ITC imported seeds of various provenances of eucalypts from CSIRO (Australia) in the years 1986, 1990, 1994 and 1995. The company established provenance trials in southern part of the country. Plus trees of *E. camaldulensis* and *E. tereticornis* were selected from such provenance trials. Selected plus trees were propagated vegetatively from coppice cuttings in mist chambers. Root trainer technology was adopted for the production of plants. The successful ramets were planted in gene banks. Promising clones were shortlisted for growth, disease resistance and pulp and paper qualities. Clonal seed orchards (CSO) adopting the permutated neighbourhood design (Sekar et al., 1984) were established.

In 1995, IFGTB initiated a coordinated programme for eucalypts with fresh introductions of a wide genetic base from natural provenances of these species (Doran et al., 1996; Varghese et al., 2008). Provenance resource stands (PRSs) of three Queensland provenances of *E. camaldulensis*, Kennedy River, Morehead River and Laura River (Doran and Burgess, 1993) were planted using bulked seed of these individual provenances. Progeny trials were established using family seedlots collected from selections made in existing southern Indian provenance trials of both species (Varghese et al., 2001). At the same time, new provenance-progeny trials of *E. camaldulensis* were planted at three locations to establish a broad, pedigreed genetic base for the breeding programme. Smaller progeny trials of *E. tereticornis* were also planted. These trials were evaluated to identify suitable provenances for different locations (Varghese et al., 2000). After evaluation, the trials were selectively thinned for conversion to first generation seedling seed orchards (SSOs). The SSOs, SPAs and PRSs incorporate many thousands of trees of known natural provenance. Together, they comprise a large base and breeding population for genetic improvement of *E. camaldulensis* and *E. tereticornis* in southern India (Varghese et al., 2008). Apart from the production of high-quality seed and ongoing genetic improvement of the breeding populations, the improvement programme also envisages deployment of outstanding individual selections in clonal plantations.

FRI initiated establishment of seed source evaluation trials of *E. camaldulensis* and *E. tereticornis* at various locations in northern part of the country. Similarly, in a provenance trial of *E. camaldulensis*, six seed sources from Australia were evaluated at Seothi (Haryana), a semi-arid region of India. At the age of eight years, two seed sources, viz., Emu Creek Petford, QLD and Laura River, QLD ranked first and second
for height and survival (Ginwal et al., 2004b). Similarly, provenance trials with 14 provenances in *E. camaldulensis* conducted at two locations in drier tracts of Shimoga district by the Mysore Paper Mills Ltd., Shimoga also revealed that Emu Creek, Petford, QLD, Irvine Bank, QLD, Gibb River, WA, and Katherine, NT had promising growth rates (Chandra et al., 1994).

Thirteen provenances of *E. tereticornis* representing 91 families from Australia and Papua New Guinea were evaluated up to the rotation age; i.e., 10 years in a combined provenance-progeny test established at three locations. In general the north Queensland provenances performed better and in particular two provenances, viz., Walsh River, QLD and Burdekin River, QLD ranked the best. The performance of local seed source was inferior to the Queensland provenances. No geographic clonal variation pattern was observed. Age-age genetic and phenotypic correlations between heights and diameters were highly significant and positive. Heritability (narrow sense) values were intermediate for height and diameter at breast height in comparison to number of branches and clean stem height. The relative performance of the top ranking provenances was consistent throughout age (Ginwal et al., 2004a).

In another evaluation trial conducted in the state of Punjab, five provenances of *E. tereticornis* obtained from CSIRO, Australia revealed that provenances of Laura areas and 20 km North of Mount Mollowy were significantly different from the provenance of Kennedy River for tree height and diameter at breast height. Similarly in a Provenance trial of *E. tereticornis* undertaken in Ferozepur Forest Division, Punjab in August, 1982 with 20 provenances revealed that Lekeland downs and Kennedy River 0.34 km N of Laura provenances of *E. tereticornis* were significantly superior to all other provenance in terms of volume production (Kapur and Dogra, 1987a). In case of *E. camaldulensis*, Gilbert River provenance revealed the highest basal area and volume (Kapur and Dogra, 1987b).

Results from different provenance trials indicated the superiority of the northern provenances of both the species of eucalypts to the southern provenances (Ghosh et al., 1977). Provenance trials of *E. tereticornis* established in many countries indicate a significant superior performance of north Queensland provenances particularly Kennedy River in India (Chaturvedi et al., 1989, Ginwal et al., 2004b) and China (Zhou and Bai, 1989), Laura and Cooktown provenance performed better in Brazil (Timoni et al., 1983), Mount Garnet and Laura, in Bangladesh (Davidson and Das, 1985), etc. The local *Eucalyptus* hybrid seedlots performed poorly in comparison to the ‘Petford’ and ‘Katherine’ provenances of *E. camaldulensis* and ‘Laura River’ and ‘Kennedy River’ seedlots of *E. tereticornis* (Chaturvedi et al., 1989).

The various trials so far conducted clearly indicate the superiority of Queensland seedlots in northern and southern parts of the country and suggest that the next generation *E. camaldulensis* and *E. tereticornis* breeding population should be comprised primarily of selections from the best Queensland provenances (Ginwal et
petford (queensland) provenance was reported to perform well across several trials conducted by the eucalyptus research centre in andhra pradesh where the annual rainfall is around 800 mm (chaturvedi et al., 1989). improved performance of several native provenances over the local land races demonstrated in provenance trials of _e. camaldulensis_, _e. grandis_, _e. microtheca_ and _e. tereticornis_ reveals that significant improvement could be made by using selections from provenances like petford, gilbert river, kennedy river and morehead river of _e. camaldulensis_ and helenvale provenance of _e. tereticornis_ (varghese et al., 2001).

6. inter and intra-specific hybridization

fri was the pioneer institution in initiating hybridization programme in eucalypt species. for the genetic improvement of eucalypts, hybridization work involving different parent species was initiated during 1966. a series of f1 hybrids, popularly known as fri-4, fri-5 to fri-15, were developed by using different species combinations.

based on the information available on crossability pattern in the genus, several hybrid combinations were synthesized to increase the productivity. certain hybrid combinations, viz., fri-4, fri-5, fri-10, fri-15 and fri-16 have displayed a very high degree of hybrid vigour under dehradun condition and produced three to five times more volume of wood than parent species (venkatesh and sharma, 1977a, b, 1979, 1980). second and third generation trials of fri-4, fri-5, fri-15 and fri-16 have been laid out in the field to assess their growth performance. promising recombinants have been selected from second and third generation trial for clonal multiplication. besides this, spontaneous f1 hybrids were picked up using morphological genetic markers. the accession numbers, their parental identity and the year in which these were developed/identified are given in table 1.

some of the hybrids described above have been clonally multiplied through tissue culture and deployed in the field under different eco-climatic conditions at bithmeda, dehradun, haldwani, hoshiarpur, hissar, jodhpur, meerut and pantnagar for evaluation of their performance. the performance of some of the hybrids with respect to growth and wood characters has been described hereunder:

(a) _f1_ hybrids _e. tereticornis x e. camaldulensis_ (fri-4) and _e. camaldulensis x e. tereticornis_ (fri-5): in a pilot field trial established in 1972-73 at dehradun, these hybrids have displayed hybrid vigour in respect of height and diameter and so in standing tree volume. an assessment made at age four years has shown that _f1_ hybrids showed three fold superiority over their parental control and double to mysore gum (mysore hybrid) in mean standing volume. _inter se_ comparison of the two hybrids has shown that fri-5 is significantly superior in growth parameters to fri-4 (ginwal and sharma, 2007).
Table 1. Interspecific controlled and natural hybrids developed at FRI, Dehradun

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Accession number</th>
<th>Parental combinations</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>FRI-2 A</td>
<td>E. tereticornis (20) X E. camaldulensis (2) (Northern form)</td>
<td>1966</td>
</tr>
<tr>
<td>2.</td>
<td>FRI-3 A</td>
<td>E. tereticornis (19) X E. camaldulensis (2)</td>
<td>1968</td>
</tr>
<tr>
<td>3.</td>
<td>FRI-4 A</td>
<td>E. tereticornis (20) X E. camaldulensis (2)</td>
<td>1970</td>
</tr>
<tr>
<td>4.</td>
<td>FRI-5 N</td>
<td>E. camaldulensis X E. tereticornis</td>
<td>1970</td>
</tr>
<tr>
<td>5.</td>
<td>FRI-6 A</td>
<td>E. tereticornis (14) X E. grandis (6)</td>
<td>1971</td>
</tr>
<tr>
<td>6.</td>
<td>FRI-7 A</td>
<td>E. tereticornis (19) X E. grandis (6)</td>
<td>1973</td>
</tr>
<tr>
<td>7.</td>
<td>FRI-8 A</td>
<td>E. tereticornis (17) X E. grandis (6)</td>
<td>1974</td>
</tr>
<tr>
<td>8.</td>
<td>FRI-9 A</td>
<td>E. tereticornis (16) X E. grandis (6)</td>
<td>1974</td>
</tr>
<tr>
<td>9.</td>
<td>FRI-10 N</td>
<td>Putative hybrid (natural, reciprocal of FRI-6)</td>
<td>1974</td>
</tr>
<tr>
<td>10.</td>
<td>FRI-13 A</td>
<td>(E. camaldulensis X E. tereticornis) X E. grandis</td>
<td>1976</td>
</tr>
<tr>
<td>11.</td>
<td>FRI-14 N</td>
<td>E. torelliana X E. citriodora</td>
<td>1976</td>
</tr>
<tr>
<td>12.</td>
<td>FRI-15 N</td>
<td>E. citriodora X E. torelliana</td>
<td>1976</td>
</tr>
<tr>
<td>13.</td>
<td>FRI-16 A</td>
<td>E. tereticornis X E. camaldulensis (Southern form)</td>
<td>1997</td>
</tr>
</tbody>
</table>

Note: Numerals within the parentheses denote the tree numbers.
A-Artificially cross-pollinated.  N-Naturally pollinated

(b) F₁ hybrids of E. tereticornis x E. grandis (FRI-6) and E. grandis x E. tereticornis (FRI-10): The F₁ hybrids between E. tereticornis and E. grandis were found intermediate to parent species. These interspecific hybrids though intermediate to parental species in more than half of the total number of contrasting characters studied (Venkatesh and Sharma, 1979) but is of interest because it involved E. grandis and E. tereticornis, the two parent species, the former shows faster rate of growth, good stem form, provides best quality of pulp and prefers high rainfed areas while, the latter is drought tolerant and thus it is very likely that hybrids may be suited for intermediary zones (hybrid habitat).

(c) F₁ hybrids of E. torelliana x E. citriodora (FRI-14) and E. citriodora x E. torelliana (FRI-15): These F₁ hybrids have shown a very high degree of sustained hybrid vigour in respect of height and diameter, the two major parameters contributing towards wood yield. An assessment made at age 9½ years has revealed that hybrids were superior to parent species, viz., E. citriodora by 464.2 per cent and E. torelliana by 99.4 per cent with regard to volume of wood produced (Ginwal and Sharma, 2007).

7. Evaluation of F₁ and F₂ and F₃ Hybrids for Wood Properties

(a) Specific Gravity
Wood properties of F₁ reciprocal hybrids of E. citriodora and E. torelliana were studied at FRI at the age 6½ years by taking cores from increment borer. The
results have shown (Table 2) that specific gravity of F₁ hybrids was in the range of 0.5619 (\textit{E. torelliana} x \textit{E. citriodora}) and 0.6161 (\textit{E. citriodora} x \textit{E. torelliana}), whereas the specific gravity of parent species was 0.6599 (\textit{E. torelliana}) and 0.9253 (\textit{E. citriodora}). The F₁ hybrids showed intermediate specific gravity of wood as compared to parents (Kapoor, 1992). Pryor \textit{et al.} (1956), reported that wood properties of most 	extit{Eucalyptus} hybrids were intermediate or the same as the parents, and seemed to be under multiple factor control.

The second and third generation hybrids (F₂ and F₃) of \textit{E. citriodora} and \textit{E. torelliana} were also subjected to studies on wood properties (Verma \textit{et al.}, 2001). The specific gravity of wood for \textit{E. torelliana}, \textit{E. citriodora}, F₁, \textit{E. citriodora} x \textit{E. torelliana}, F₂, \textit{E. torelliana} x \textit{E. citriodora} and F₃, \textit{E. citriodora} x \textit{E. torelliana} was found to be 0.6521, 0.8535, 0.6328, 0.5697 and 0.5604, respectively (Verma \textit{et al.}, 2001). Highest specific gravity of wood was exhibited by \textit{E. citriodora} and the lowest values for the same were observed in segregating populations (F₃) \textit{E. citriodora} x \textit{E. torelliana}. The F₂ populations of reciprocal hybrids of \textit{E. citriodora} x \textit{E. torelliana} showed intermediary values as compared to parental progenies.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{S. no.} & \textbf{Material} & \textbf{Specific gravity} & \textbf{Fiber length (m\textmu)} & \textbf{Wall thickness (m\textmu)} & \textbf{Lumen diameter (m\textmu)} \\
\hline
1. & F₁ \textit{E. citriodora} x \textit{E. torelliana} & 0.6161 & 1291.4 & 4.70 & 6.55 \\
2. & F₁ \textit{E. torelliana} x \textit{E. citriodora} & 0.5619 & 1168.0 & 4.15 & 10.65 \\
3. & \textit{E. citriodora} & 0.9253 & 970.8 & 6.66 & 8.15 \\
4. & \textit{E. torelliana} & 0.6599 & 1069.8 & 5.46 & 8.91 \\
\hline
\end{tabular}
\caption{Wood properties of \textit{Eucalyptus} F₁ hybrids, \textit{E. citriodora} and \textit{E. torelliana} at age of 6½ years}
\end{table}


(b) Fibre Characters
The F₁ reciprocal F₁ hybrids of \textit{E. citriodora} and \textit{E. torelliana} had longer fibre length, less wall thickness as compared to parent species (Table 2). The F₁ hybrids of \textit{E. citriodora} x \textit{E. torelliana} and \textit{E. torelliana} x \textit{E. citriodora} have shown longest fibre length (1,291.4 m\textmu) and widest lumen diameter (10.65 m\textmu) as compared to parent species. So far as the wall thickness is concerned both the reciprocal hybrids have registered the lowest value as compared to parent species which is of interest from pulping and paper making point of view.

Fibre studies carried out on F₂ and F₃ generation hybrids of \textit{E. citriodora} x \textit{E. torelliana} have shown some plants which recorded higher values for fibre length,
fibre width and lowest value for lumen diameter as compared to parent species (Verma, 1998). In $F_2$ generation of $E. \text{citriodora}$ and $E. \text{torelliana}$, the highest values recorded for fibre length, fibre width were 1,245.32 \( \mu \text{m} \) and 18.43 \( \mu \text{m} \) respectively while in $F_3$ $E. \text{citriodora} \times E. \text{torelliana}$ the lowest value recorded for fibre wall thickness was 4.60 \( \mu \text{m} \). However maximum lumen diameter was recorded in $F_3$ $E. \text{citriodora} \times E. \text{torelliana}$. All these parameters, besides others like kappa no, etc. are of great significance which contribute a lot to the quality of paper. Longer fibre will presumably lead to increase in higher tear index. It also affects the physical properties of the sheet such as the strength and rigidity, especially tearing strength which decreases with decrease fibre length.

During 1996, the IFGTB with the technical support of Australia Tree Seed Centre (ATSC), CSIRO initiated a genetic improvement programme in $E. \text{camaldulensis}$ and $E. \text{tereticornis}$. Experiments were carried out to develop dihybrid combinations such as $E. \text{camaldulensis} \times E. \text{tereticornis}$, $E. \text{tereticornis} \times E. \text{grandis}$ and $E. \text{tereticornis} \times E. \text{alba}$ and $E. \text{tereticornis} \times E. \text{urophylla}$. The hybrids developed and tested in the R and D paper testing laboratories of M/S TNPL and M/S ITC Ltd. Two collaborative research projects aiming for production of dihybrid seeds in $Eucalyptus$ and $Corymbia$ were initiated by IFGTB with M/S TNPL and M/S ITC Ltd. during 2010 and 2011, respectively. The projects were envisaged to deliver hybrid seeds for developing high yield hybrid selections to support the ever increasing demand of paper pulp. As a pioneering event IFGTB was able to supply hybrid seeds to industrial forestry to widen the scope of selection and improve productivity (Source: IFGTB Coimbatore).

In addition to FRI and IFGTB, private industries like ITC Ltd. also developed intra-specific hybrids through reciprocal crosses between some of the promising clones of $E. \text{tereticornis}$ and inter-specific hybrids between selected clones of $E. \text{tereticornis}$ and candidate plus trees of other species of eucalypt (Piare Lal, 2001). In ITC Ltd., the hybridization programme was initiated in 1994 and a breeding orchard was setup with $E. \text{alba}$, $E. \text{camaldulensis}$, $E. \text{grandis}$, $E. \text{tereticornis}$ and $E. \text{urophylla}$. Inter-specific hybrids using parental combinations, viz., $E. \text{tereticornis} \times E. \text{urophylla}$; $E. \text{tereticornis} \times E. \text{grandis}$; $E. \text{tereticornis} \times E. \text{camaldulensis}$; $E. \text{tereticornis} \times E. \text{alba}$ and $E. \text{tereticornis} \times E. \text{torelliana}$; $E. \text{urophylla} \times E. \text{grandis}$ were attempted. Major attention was focused on development of control pollinated hybrids followed by cloning of individual outstanding hybrids showing good heterosis. A large number of hybrid clones developed from hybrid trees with good heterosis, were evaluated in Andhra Pradesh and Punjab. Some of the most promising hybrid clones tested in Punjab are 2004, 2007, 2012, 2013, 2023, 2045, 2049, 2070, 2155, 3011, 3012 and 3018. Some of these clones like 2070 and 2045 are already being planted on large scale (Piare Lal, 2001). Hybrids of $Eucalyptus$, viz., teretigrandis ($E. \text{tereticornis} \times E. \text{grandis}$) and
urograndis (*E. urophylla x E. grandis*) have adapted well to drought conditions and are producing maximum volume of wood. These hybrids are now planted on large scale (Piare Lal, 2001).

8. Vegetative Propagation

Rooting of juvenile cuttings has great potential in improving the forest productivity. Leafy cuttings taken from very young seedlings or shoots developed from lignotubers of most eucalypt species can be easily rooted in sand with bottom heat in about two to three weeks (Pryor and Willing, 1963). However, the capacity to root by the cuttings declines very rapidly as the plants become older. In most of the species it becomes non-existent when they have passed the 15 leaf pairs stage. For species, which do not coppice readily such as *E. deglupta*, application of IAA and IBA promotes profuse coppicing on cut stumps (Davidson, 1977; Venkatesh, 1986), which then can be used for rooting purposes.

In India, work on clonal propagation of eucalypt was taken up by different organizations, viz., ITC Bhadrachalam Paper Board Ltd., TERI and institutes under Indian Council of Forestry Research and Education (ICFRE). ITC Bhadrachalam Paper Board Ltd. has used the technology for production of clonal material on commercial basis using the selected clones. More than 200 plus trees, selected based on desirable phenotypic characters, were cloned and significantly large differences in growth rates and disease resistance capacity of different clones was noticed in the field trials (Piare Lal, 1994). While ICFRE institutes under World Bank project (FREEN) established vegetative multiplication gardens (VMG) of various eucalypt species by assembling hedges of selected candidate plus trees (CPTs). The hedges were maintained in hedge gardens and produce juvenile shoot cuttings which gives 40-70 per cent rooting under mist condition and controlled temperature.

Rooting of leafy cuttings of eucalypt species/hybrids have been successfully achieved (Vakshasya and Rawat, 1984; Chandra *et al*., 1988; Gurumurthi *et al*., 1988). The advances made in the techniques of vegetative propagation of eucalypts are revolutionary from a tree breeding point of view as these help in deployment of the improved material in the field and utilize the genetic gains of tree breeding.

Propagation of more than a dozen species/hybrids of eucalypt adopting tissue culture (micropropagation) technique has been successfully tried from juvenile as well as mature trees. At FRI, protocols for tissue culture of candidate plus trees (CPTs) of *E. tereticornis* (Bisht *et al*., 2000b), promising hybrids of *Eucalyptus*, viz., *E. tereticornis x E. camaldulensis* (Chauhan *et al*., 1996), *E. camaldulensis x E. tereticornis* (Bisht *et al*., 2000a) and reciprocal hybrids of *E. citriodora* and *E. torelliana*, (Kapoor and Chauhan, 1992; Bisht *et al*., 2002) and FRI 16 *E. tereticornis x E. camaldulensis*, southern form (Bisht *et al*., 1999) have been
developed. The plantlets developed through tissue culture of F₁ interspecific hybrids were used to establish hedge garden and subsequently used for clonal propagation (Uniyal, 2002).

By application of the techniques mentioned above, rapid genetic improvement with higher yield of wood, both in terms of qualitative and quantitative traits, may be achieved under commercial management, if they are applied judiciously.

9. Plus Tree Selection and Clonal Testing

Productivity and profitability of plantations of eucalypts have been revolutionised with the development of genetically improved, fast growing and high yielding clonal planting stock. A comprehensive programme was initiated in south India by ITC Ltd. for the selection of superior trees with desirable characteristics such as straightness of stem, growth, disease resistance, etc. Trees were selected from government (Andhra Pradesh Forest Development Corporation - APFDC) and farmers’ plantations. Initially a total of 64 candidate plus trees (CPTs) of *E. tereticornis*, *E. camaldulensis* and *Eucalyptus* hybrid (Mysore gum) were selected during 1989, later on this number reached to 650 CPTs and 247 full sib CPTs. These trees were further cloned and evaluated in the field. A total of 86 promising clones were shortlisted from the field trials. Out of 86 promising clones of ITC, 54 (63 per cent) have come from the provenance seeds source obtained from CSIRO, Australia and 32 (37%) from local Mysore gum (Kulkarni and Lal, 1995; Kulkarni, 2001). The provenance that gave maximum clones are 8 km NW Black Mountain and 1 km N of Laura. Clones were evaluated for comparative genetic superiority and G x E interactions. Nearly 123 trial plots in a 29 ha area have been established since 1989 in various soil types by the company. For ensuring wide and diverse genetic base of clones, more than 1,000 CPTs have been cloned and tested in field trials for evaluating their comparative genetic superiority and adaptability to different soil types. Eucalypt clones like 3, 6, 7, 10 and 27 developed at Bhadrachalam formed the basis of initial clonal plantations since 1992. However, clones 72, 105, 286, 288, 316, 407, 411, 413, 498 and 526 and hybrid clones 2004, 2012, 2045, 2049, 2070, 2155 are highly productive commercial clones with excellent bole form which are now being planted on large scale. Out of these clones 411, 413 and 526 have high tolerance and adaptability to alkaline soils followed by clones 72, 105, 288 and 316. Clones 1, 99, 128, 130, 271, 272, 275 and 276 are also fairly tolerant to alkaline soils. In addition to clones listed above, clones number 265, 266, 274, 284, 290 and 292 and hybrid clones 2011, 2050, 2052, 2120, 2121, 2149 and 2156 are popular in Andhra Pradesh (Kulkarni and Piare Lal, 1995; Piare Lal et al., 1997; Kulkarni, 2006).

About fifty good trees were selected from the four outstanding Australian provenances (Kennedy River, Laura River, Mt. Carbine and Lake Land-down) identified in two provenance trials of *E. tereticornis* located at Pudukkottai and
Karaikudi in Tamil Nadu state (Kumaravelu et al., 1995). Seeds from the selected trees were used to establish seedling seed orchards cum progeny trials at two locations; i.e., Pondicherry (11° 55' N latitude, 79° 52' E longitude, 1250 mm rainfall) and Pudukkottai (10° 23' N latitude, 78° 49' E longitude, 650 mm rainfall) in South India. These seed orchard served as a useful asset for meeting the immediate seed requirement of the Tamil Nadu Forest Plantation Corporation.

Superior trees of *E. camaldulensis* and *E. tereticornis* in south India were also identified by IFGTB in the provenance progeny trials and in SPAs using phenotypic selection (Hegde and Varghese, 2002). Approximately 126 best trees of the top-ranking trees in un-pedigreed and pedigreed orchards at different locations were vegetatively propagated for establishing clonal trials. These trees were clonally propagated and field tested to select promising clones which might out-perform seed of the best natural provenances and clones that were commercially available from other improvement programmes.

During the World Bank funded ‘FREE Project’ a comprehensive selection and evaluation programme on 11 forest tree species across the country was carried out and *Eucalyptus* was one of them. Following standard guidelines, ICFRE institutes, viz., FRI, AFRI and IFGTB were involved in the selection of CPTs. A total of 50 CPTs of *E. camaldulensis* were selected from the state of Punjab, 150 CPTs of *E. tereticornis* were selected from U.P. and Uttarakhand and 100 CPTs of *Eucalyptus* sp. were selected from Tamil Nadu. Many of these CPTs were cloned and deployed in seed orchards and vegetative multiplications gardens. Some of the seed orchards established with the selected trees are in the stage of seed production. In Punjab, plus trees were also selected by the Punjab Agricultural University in plantations at farmers’ field with comparison tree method (Sidhu, 1993). Only those trees were selected as plus trees which had height more than 20 per cent; diameter more than 35 per cent; and volume more than 150 per cent over the average of their respective comparison trees. Thirty one plus trees were selected and of them only 16 were progeny tested. Eleven progenies excelled, one equalled and four were below the control in seedling height. A maximum of 51.3 per cent more height than the control was observed in the progeny of plus tree number 17.

Average productivity of commercial eucalypt clones is around 20 to 25 m³ ha⁻¹ yr⁻¹, under un-irrigated conditions. However, many farmers have achieved record growth rates of 50-58 m³ ha⁻¹ yr⁻¹ making farm forestry an economically attractive land use option (Piare Lal, 1994). Significant improvements in quality of produce and reductions in per unit production costs have also been possible with the use of true to type, uniform and genetically improved clonal planting stock of eucalypt (Piare Lal, 2001).

Clonal testing and release programmes in forest trees got a big boost after the development of the guidelines for ‘testing and releasing of tree varieties and clones’ by ICFRE during the year 2008. Following these guidelines IFGTB made a comparative
study and released four clones of *E. camaldulensis* for cultivation in farmlands. Demonstration clonal plantations of the released four clones were established. Efforts were also made to improve the quality of the seeds through progeny testing and establishment of clonal and seedling seed orchards. Further, through systematic selection and multilocation testing, one clone of *Eucalyptus* hybrid (FRI-EH-001) (*E. camaldulensis* Dehn. x *E. tereticornis* Sm.) developed by FRI was released by the Variety Release Committee of Ministry of Environment and Forests, Govt. of India in the year 2011. The clone has a productivity of more than of 30 m$^3$ ha$^{-1}$ yr$^{-1}$. To facilitate registration of these new clones, guidelines for distinctness, uniformity and stability (DUS) testing in eucalypt have been developed.

### 10. Production of Genetically Improved Seed

Selection and management of seed production areas is a commonly adopted strategy representing the first stage of tree improvement, after selection of the best species and provenances. Such seed production areas could be stands specially planted for seed production or they could be existing stands specially managed for seed production, provided their genetic origin is appropriate. Collection of seed from better than average stands which have been thinned early to remove inferior trees and to promote development of large crowns capable of heavy seed production is often the quickest and best interim measure to meet the need of large quantity of seed of known origin and with some genetic improvement.

Seed orchards are a means of obtaining large quantities of genetically improved seeds relatively cheaply by allowing selected outstanding trees (plus trees) or their progeny to cross. Cuttings from the plus trees are used to establish clonal seed orchards or seedlings raised from seed collected from the plus trees are used to make seedling seed orchard. In both cases, the orchards are isolated and managed for seed production. The seeds are produced by cross-pollination among the outstanding clones or progenies planted at a single plot. Seedling seed orchards have been commonly used as production populations in breeding programs for short rotation tropical eucalypt (Eldridge *et al.*, 1994). Seed orchards are expected to generate genetically good seeds and constitute a reliable, controllable and reproducible seed source. Depending on the fertility and mating pattern in the orchard trees, the seed crop may vary in diversity and vigour. Gains up to 20 per cent are anticipated over and above those from provenance selection once the pedigreed breeding population gets converted to a seedling seed orchard (Doran *et al.*, 1996). The gain expected from thinned unpedigreed seedling seed orchards is about the same as that obtained from a first generation pedigreed seedling seed orchard of the long term breeding programme (Shelbourne, 1992).

The IFGTB established pedigreed and unpedigreed seedling seed orchards in representative sites in south India to evaluate the growth performance of the seedlots
followed by thinning of inferior trees for quality seed production (Hegde and Varghese, 2002). Natural seedlots of *E. tereticornis* have poor flowering in peninsular India (Pinyopusarerk and Harwood, 2003a). Poor flowering has also been observed in the ramets of *E. tereticornis* established in clonal seed orchards in north India, particularly in Haryana and Uttarakhand, that is resulting in poor seed production from the seed orchards. Poor and irregular flowering is often observed in orchards that are not located on good flowering sites, and even on good sites, micro-site influences are important (Sweet, 1992).

Depending on the fertility and mating pattern in the orchard trees, the seed crop may vary in diversity and vigour. Fertility variation in seedling seed orchard of *E. tereticornis* and *E. camaldulensis* in south India was studied at moist and dry sites at eight and nine years of age by Kamalakannan *et al.* (2007). *E. camaldulensis* on the moist location had 73 per cent fertile trees and low fertility difference at eight years, whereas, only 23 per cent trees were fertile in the *E. tereticornis* orchard at the same site and the fertility variation was high. In the dry location, fertility was almost the same in both species (Kamalakannan *et al.*, 2007). High fertility variation has also been reported in a pedigreed *E. tereticornis* seedling seed orchard in Tamil Nadu (Varghese *et al.*, 2002). High fertility variation in eucalypt seedling seed orchards particularly *E. tereticornis* indicate that eucalypts introduced to exotic environments are more variable (Kamalakannan *et al.*, 2007) and a cautious approach need to be adopted in selection and deployment of families in seedling seed orchards.

Demand for genetically improved seed and clonal material for establishment of eucalypt plantations is increasing day by day. There is a need for coordinated efforts in establishment of intensively managed seed orchards; clonal selection and testing across the country so that the site-specific well adapted productive clones of eucalypts are made available to the growers. Financial support from the industries, particularly paper, pulp and plywood in addition to government, is extremely important in promotion and improvement of eucalypt in the country. Eucalypt is a tree with great environmental values. This well-managed asset is a driver of economic and social development of the country as it provides us with one of the best options for handling deforestation and is hugely beneficial to the society.

References


