



## Raising Sustainable Pulpwood Plantations for Feedstock



**Dr. K. Jayakumar\***  
General Manager (Plantation)



**Dr. V. Prasath \***  
Chief Manager (Plantation)



**Dr. P. Chezhan\***  
Chief Manager (Plantation)



**Dr. G. Ravi \***  
Assistant General Manager (Plantation)



**P. Leena Rosy\***  
Assistant Manager (Plantation)

\*Tamil Nadu Newsprint and Papers Limited, Kagithapuram, Karur

**Abstract:** The implementation of the national forest policy, the small landholding pattern, and the highly fragmented nature of farmlands have made the Indian pulp and paper industries a significant focus of farm forestry in the past three decades. TNPL has raised plantations on 1.13 lakh ha of farmlands so far and is expanding at the rate of 12,000 ha annually. Currently, TNPL holds 28,637 ha of FSC-certified plantations consisting of Casuarina and Eucalyptus as major species. Adapting genetically improved varieties, quality planting stock, precise silvicultural operations and effective pest control are the basic principles for intensively managed plantations. At TNPL, by adapting improved genetic sources, about a twofold increase in pulpwood yield with Casuarina species and an 11.56% increase with Eucalyptus species has been obtained compared to conventional genetic sources. Fertilizer applications for the pulpwood plantations were optimized to achieve maximum yield in short rotations. The ideal choice of microbial cultures applied during the plant propagation stage has translated into disease-free plantations in the field. Integrating the scientific and technological advancements in the nursery, as well as in the field, resulted in eco-friendly and climate-smart planted forestry in the state of Tamil Nadu.

**Keywords:** pulpwood plantations, Casuarina, Eucalyptus, fertilizer application, sustainable pest control, ecosystem services

### Introduction

Agroforestry in India is gaining increasing significance, due to its potential to enhance household consumption, sustainable income generation and improve the livelihood of smallholding farmers. In southern India, the cultivation of short-rotation Casuarina, Eucalyptus and Melia dubia has become a widespread practice among smallholding farmers. Farmers predominantly favor the cultivation of Eucalyptus and Casuarina under rainfed and irrigated conditions, respectively, due to their rapid growth rate, high annual yield per unit area, strong coppicing ability (Eucalyptus and Melia dubia), low maintenance requirements, high market demand at competitive prices, and adaptability to diverse soil and climatic conditions (Ghale et al., 2022).

The agroforestry plantations serve as a critical input for many industries, while also functioning as a safety net during periods of wood insecurity. Notably, the pulp and paper industries rely on small-scale landholdings for raw material sustainability, which has led to the gradual increase of marginally utilized lands into pulpwood plantations, revealing their growing economic importance to the nation. At present, India has a total agroforestry area of about 28.43 M ha in all the 15 agro-climatic zones, with appreciable agroforestry cover (7.57%) in Southern Plateau showing an increasing trend in recent years (Arunachalam et al., 2022).

The planted forests, in other words, a collection of many smallholding plantations are much closer to industrial agricultural crops than either native forests or traditional agricultural crops, as they need a different set of management practices. To maintain uniformity and to obtain high yields, they require quality planting stock, preparation of soil, fertilization, weeding, pest control and in some cases, like Casuarina, one time pruning. Once the plantation trees reach a certain age, they control weeds and retain more soil moisture as a result of increased shade and accumulation of leaf litter on the ground. It is for this reason that the maintenance of plantations during the first year is crucial for increasing the pulpwood yield and wood inventory, and clear management recommendations to smallholding farmers are warranted to improve industrial farm forestry program (Jayakumar et al., 2025a).

Tamil Nadu Newsprint and Papers Limited is one of the largest pulp and paper industries in India, with an annual production capacity of 6.4 lakh MT (LMTA) of paper and paper board using wood and bagasse pulp as raw materials. The annual requirement of woody raw material is about 12 lakh LMTA, and to

source the woody raw material, around 1.13 lakh ha pulpwood plantations have been raised since the year 2004-05, mostly consisting of the species *Eucalyptus* and *Casuarina*. It has gradually introduced green technologies such as improved genetic sources and microbial biotechnology while also standardizing the spacing and fertilizer recommendations for short-rotation pulpwood plantations. This article is based on the research findings of TNPL with the objectives of (1) finding the variation in pulpwood yield among genetically improved and conventional varieties of different species, (2) optimizing the fertilizer application rate for pulpwood plantations grown in semi-arid conditions, and (3) verifying the effect of plant microbial cultures on sustainable disease control in the nursery as well as in the field after transplanting the propagules.

**Materials and methods**

**Field experiments- genetic assessment & Silviculture**

Field experiments were conducted using genetically improved new generation clones of *Casuarina* (CH1, CH2, CH4, and CH5) and *Eucalyptus* (TNPL 191, TNPL 192, TNPL 193, and C7) and compared their wood yield with that of their respective conventional clones (*Casuarina* CJ1 and *Eucalyptus* EC4). These trials were conducted in three locations: Karur District (11.06337, 77.98679), Ariyalur District (11.28649, 79.40263), and Villupuram District (12.065510, 79.753841) to confirm the test results. The actual pulpwood yield was measured after harvest and compared between the plantations from improved genetic sources and conventional genetic sources. In addition to the pulpwood yield, the measurable ecosystem service of the plantations (ecosystem carbon stock; ECS) was measured according to standard procedures (Sharma et al., 2025) for all the studied clones. Experiments to determine the ideal fertilizer to be applied to pulpwood plantations under irrigated conditions were conducted separately in the same locations. Fertigation doses of 150-100-150

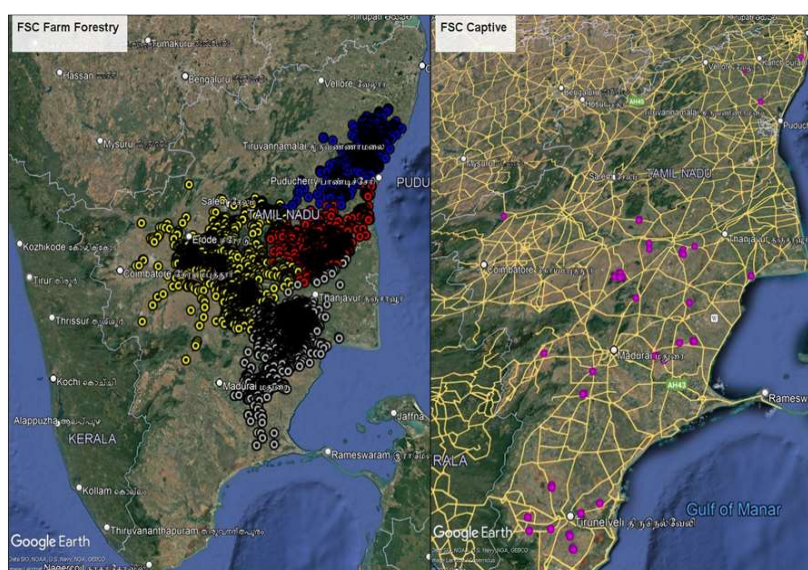
kg NPK/ha, 100-66-100 kg NPK/ha, 75-38-75 kg NPK/ha, and 50-33-50 kg NPK/ha applied in four equal splits for two years through drip irrigation, were compared against a treatment with no fertilizers in *Casuarina* plantations consisting of three clones, planted in a spacing of 1.5 m × 1.2 m. Similarly, the fertigation doses of 125-83-125 kg NPK/ha, 100-66-100 kg NPK/ha, and 75-50-75 kg NPK/ha applied in four equal splits for two years were studied in *Eucalyptus* plantations consisting of five clones, planted at 2 m × 1.2 m, and compared to the non-fertilized plantations. A *Melia dubia* plantation with the superior trait GK-10, planted in 3 m × 1.5 m configuration, was studied for optimization of fertilizer application (200-100-200, 150-75-150, 100-50-100 kg of NPK/ha) and compared to that of the control (no fertilization).

**Field experiments- disease control**

The inclusion of microbial cultures for plant protection (*Trichoderma viride*) and plant growth promotion (arbuscular mycorrhizal fungi, *Frankia*, and *Micromonospora* spp.) was studied in the nursery. Disease incidence in the microbial culture-inoculated and non-inoculated plantations was assessed. The strains of the inoculants, viz., *T. viride* (IFGTB 15), *Micromonospora* (MK271738), and *Frankia* (CeCo1) were obtained from the Indian Council for Forestry Research and Education- Institute of Forest Genetics and Tree Breeding (ICFRE - IFGTB), subcultured in the laboratory, and mass cultured using fermentors. All these cultures were inoculated into the rooting substrate (coir pith, a coconut residue, pretreated with *Pleurotus sajor-caju*) prior to the planting of *Casuarina* and *Eucalyptus* vegetative cuttings. The conventional practice of applying fungicide (Carbendazim, 0.2% w/v) was studied as a control treatment. Prior to inoculation of the cultures and after the pretreatment of the medium, the vascular arbuscular mycorrhizae (*Glomus* spp.) were also infused into the rooting substrate. The disease incidences were observed in the nursery as well as in the farm plantations after transplanting the propagules.

**Table 1. FSC-certified plantations of TNPL (in hectares, until Dec 2025)**

Year	<i>Casuarina</i> hybrids		<i>Eucalyptus</i> hybrids		<i>Gmelina arborea</i>	<i>Melia dubia</i>	<i>Leuceana leucocephalla</i>	Total
	Farm forestry	Captive plantations	Farm forestry	Captive plantations				
2025-26	859.28		375.27					1234.55
2024-25	4220.68		5153.02	24.21				9397.91
2023-24	4715.48		3380.5	115.25				8211.23
2022-23	2670.25		2896.34	977.1			2.02	6545.71
2021-22			1634.6	119.49	4.86			1758.95
2020-21		19.03	850.24	204.62	12.15	3.02	0.82	1089.88
2019-20		27.18		140.49				167.67
2018-19				10.93				10.93
2016-17				216.89				216.89
Total	12465.69	46.21	14289.97	1808.98	17.01	3.02	2.84	28633.72



**Fig. 1. Maps showing the FSC-certified farm forestry and captive plantations of TNPL.**

## Results and Discussion

### Effect of improved genetic sources on pulpwood plantations

The introduction of improved genetic sources (IGS) in pulpwood plantations (high-yielding short-rotation hybrids) substantially improved the pulpwood yield and carbon assimilation pattern compared to conventional genetic sources (CGS; Fig. 2). A More pronounced impact is observed in Casuarina hybrids compared to Eucalyptus hybrids, due to Casuarina's nitrogen-fixing ability and altered soil moisture and nutrient regimes, which are the limiting factors for Eucalyptus clones, as they are often cultivated under rain-fed conditions. Increased wood density, stand volume, total biomass, including pulpwood yield and ecosystem carbon storage with IGS could be attributed to the favorable genetic diversity found in the inter- and intra-specific hybrids and a positive interaction between clone × site conditions (Huse et al., 2018; Garg et al., 2022). Therefore, the superior performance of IGS clones favors their deployment in industrial plantations to increase the pulpwood production, as well as increase ecosystem carbon storage, leading to the development of climate-smart plantations.

The pulping analysis showed no difference between the CGS and IGS in Casuarina clones. However, the wood productivity of the plantations indicates a twofold increase with IGS compared to CGS varieties, due to the cultivation conditions adapted for Casuarina plantations: provided with irrigation and a better water and nutrient-responsive environment under semiarid conditions. In Eucalyptus, an increase of about 7.8% in basic density and about 8.18% in screened pulp yield, as well as a reduction of about 16.51% in kappa number were recorded. Therefore, deploying the Casuarina IGS clones in farm forestry plantations will provide better pulpwood yield, and the Eucalyptus IGS clones will provide better pulp quality as well as increased pulpwood yield.

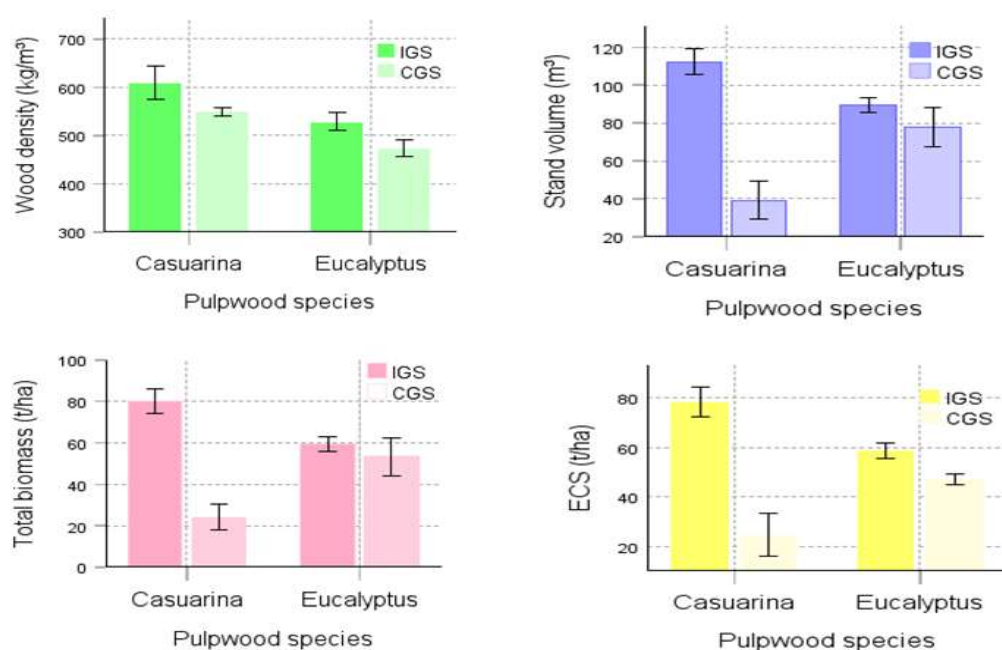


Fig. 2. Differences in growth yield and ecosystem carbon stock are observed between improved genetic sources and conventional genetic sources across the plantations.

Table 2. Analysis of pulping characteristics in Eucalyptus clones

Parameters	Unit	CGS		Mean	IGS				Mean
		C 7	EC 4		TNPL 192	TNPL 193	H 4	C 2021	
Bulk Density	kg/m <sup>3</sup>	245	227	236.00	231	216	281	280	252.00
Basic density	kg/m <sup>3</sup>	518	476	497.00	552	489	551	551	535.75
Chemical addition	%	17	18	17.50	17	18	17	18	17.50
Rejects	%	0.09	0.12	0.11	0.04	0.02	0.17	0.18	0.10
Screened Pulp yield	%	46.3	46.7	46.50	49.7	49.8	49.2	52.5	50.30
Kappa number	-	23.5	30.7	27.10	24.0	25.7	23.3	17.5	22.63

Table 3. Analysis of pulping characteristics in Casuarina clones

Parameters	Unit	CGS		Mean	IGS			Mean
		CJ9	CJ 1		CH 1	CH 2	CH 5	
Bulk Density	kg/m <sup>3</sup>	245	253	249	260	222	232	238.00
Basic density	kg/m <sup>3</sup>	592	599	595.5	686	615	553	618.00
Chemical addition	%	17	17	17	17	17	17	17.00
Rejects	%	0.32	1.1	0.71	0.41	0.54	0.37	0.44
Screened Pulp yield	%	52.3	52.8	52.55	51.2	51.9	52.6	51.90
Kappa number	-	17.6	20.1	18.85	20.0	16.6	17.2	17.93

Effect of mineral fertilizers on the pulpwood plantations

The application of mineral fertilizers is considered a means of increasing pulpwood productivity in short-rotation plantations. However, excessive application will lead to an increase in lignin-to-cellulose ratio and non-process inorganic elements in black liquor during pulp processing. Therefore, the optimum dose of fertilizers must be determined for pulpwood plantations. In general, the application of mineral fertilizers improved the pulpwood yield in all three plantations. In Eucalyptus, the application of the highest rate of fertigation (125-83-125 kg NPK/ha) resulted in achieving the highest debarked pulpwood yield in all the clones, consisting of IGS and CGS (Fig. 3). The CGS clone C-7 (Eucalyptus teriticornis) was found to have a highly fertilizer-responsive trait, followed by the IGS clone TNPL 192 (E. camaldulensis × E. camaldulensis) in semiarid conditions.

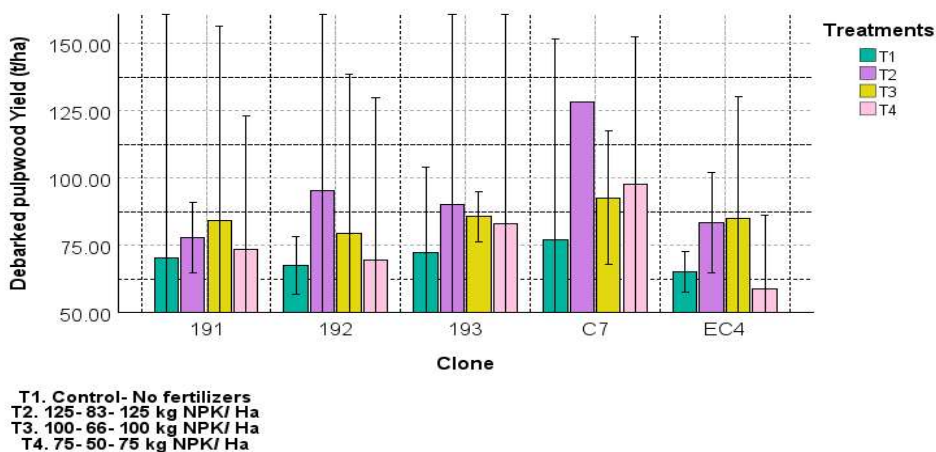


Fig. 3. Response of Eucalyptus clones to different doses of fertigation

The growth of Casuarina plantations, observed in 24-month-old stand, showed a high fertilizer response in all the clones (Fig. 4). The highest dose of 150-100-150 kg NPK/ha resulted in attaining maximum GBH, followed by 100-75-100 kg NPK/ha, maintaining statistical parity with the previously mentioned dose. The lower doses were found to be less effective for Casuarina clones. It can be seen from the figure that the fertilizer application did not affect tree height significantly, as the height parameters are mostly governed by genetic characteristics of the species (Prasad et al., 2011). Therefore, a dose of 100-75-100 kg NPK/ha is sufficient for yield increment in Casuarina plantations as they can fix atmospheric N and acquire more nutrients from the soil compare to other species. Furthermore, the results have proved that Casuarina hybrid CH5 (C. equisetifolia × C. junghuhniana) is a highly fertilizer-responsive clone compared to the species C. junghuhniana (CJ9) and C. equisetifolia (MTP2).

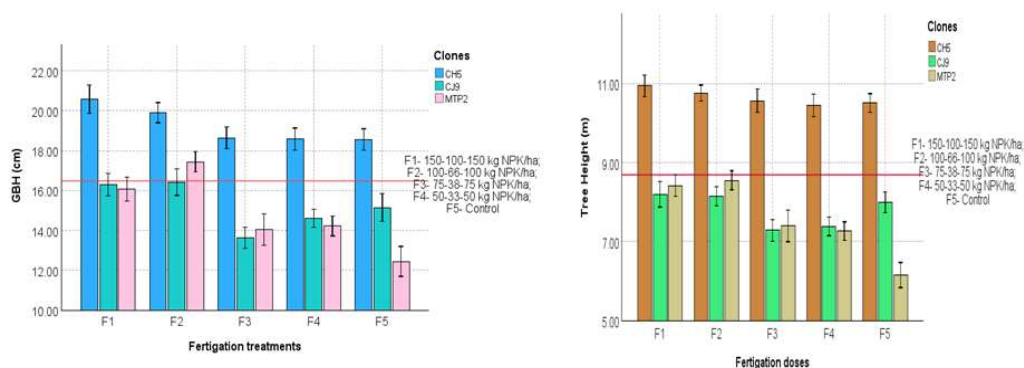


Fig. 4. Response of Casuarina clones to different doses of fertigation.

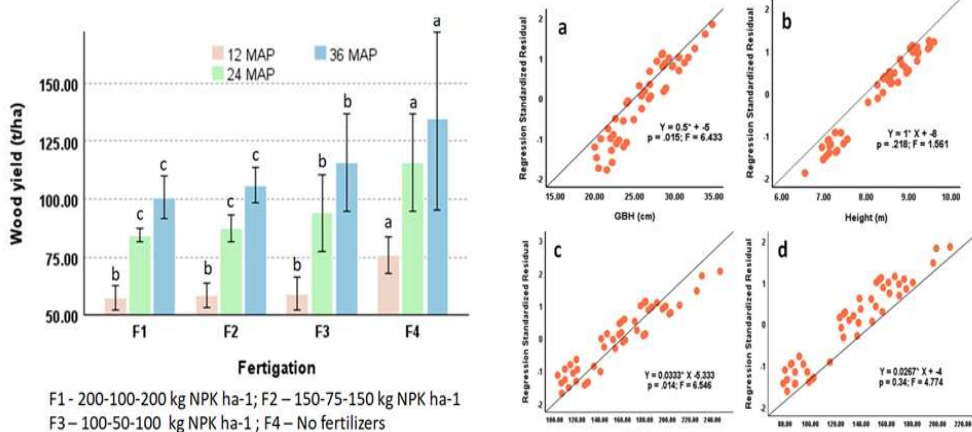


Fig. 5. Response of Melia dubia plantation to different doses of fertigation

### Sustainable disease control in the pulpwood plantations

The clones of pulpwood species Eucalyptus and Casuarina are well resistant to insect pests. However, disease incidents are prevalent in these species during their propagation and after transplanting them in the field, leading to a yield loss of 13% to over 80%, depending on specific cases. While the pathogens *Cylindrocodium* spp., *Rhizoctonia* spp., and *Pythium* spp. are associated with Eucalyptus, *Ralstonia* spp., *Phytophthora* spp., and *Fusarium* spp. often infect Casuarina (Countinho and Wingfield, 2017; Negi et al., 2024). The use of chemical fungicides is limited to a certain period and does not guarantee healthy plantations. Moreover, repeated use of chemical fungicides leads to the emergence of difficult-to-control diseases (Karthikeyan et al., 2022). Sustainable disease control in the nurseries should translate into disease-free plantations. Therefore, TNPL has adopted biological means of disease control during nursery propagation, which reflected in effective disease control under field conditions. The inoculation of VAM has resulted in better rooting of the clonal plants, resulting in better survival in the field with induced disease resistance. The liquid microbial cultures (*T. viride*, *Micromonospora*, and *Frankia*), produced using fermentors, when infused into the rooting substrate, created disease-free environment in the nursery as well as in the field plantations. With these microbial biotechnological approaches, TNPL achieved comprehensive disease control (> 95%) in clonal propagation as well as in the farm plantations.

#### A. Inoculation of liquid microbial cultures and their effects on plant quality and disease control



#### B. VAM- production, infection in the roots and profuse rooting



Fig. 6. Sustainable disease control in plantations using microbial biotechnology

### Conclusions:

The cultivation of pulpwood species in both traditional and new areas has become popular among the farmers of Tamil Nadu. The present study aimed to improve pulpwood productivity in the farmlands by introducing high-yielding clones, optimal fertilizer application, and the inclusion of microbial biotechnology. From the results of the field experiments, a fertilizer dose of 125-83-125 kg ha<sup>-1</sup> and 100-75-100 kg NPK/ha for Eucalyptus and Casuarina, respectively, at a monthly frequency for two years can be recommended for short-rotation plantations. Due to its highly fertilizer-responsive nature, the species *Melia dubia* can be fertilized with 200-100-200 kg NPK/ha to obtain a higher pulpwood yield. The application of microbial biotechnology has protected the clonal pulpwood plants against an array of diseases and has resulted in disease-free plantations. In general, adapting advancements in plantation programs, such as improved genetic planting materials, fertilization to plantations, and efficient disease control through microbial biotechnology will ensure sustainable raw material availability for pulp and paper industries, besides improving the livelihood of the smallholding farming community. Furthermore, all the wood-based industries can adopt these novel technologies for developing farm forestry plantations in their catchment areas to ensure sustainability in fiber-based production.

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