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Growth characteristics and wood qualities of less common agroforestry tree species in the semi-arid zone for the production of high-quality pulp and paper

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Abstract

The suitability of five less common agroforestry tree species—*Ailanthus excelsa*, *Eucalyptus tereticornis*, *Leucaena leucocephala*, *Melia dubia*, and *Neolamarckia cadamba*—for pulp and paper production in the semi-arid region of Bundelkhand, India, was assessed by examining their growth characteristics, wood qualities, fibre dimensions, and fiber-derived indices. The outcome showed that every attribute under study had a considerable variance. The range of all the studied growth and wood traits among five pulpwood trees were recorded for tree height (5.2-5.9 m), GBH (20-24 cm), volume (0.017-0.027 m³), biomass (8.50-15.28 kg), wood basic density (509.6-584.4 kg/m³), fibre length (819.8-1416.0 µm), fibre diameter (14.6-37.9 µm), fibre lumen diameter (7.5-29.8 µm), fibre double cell wall thickness (4.8-9.7 µm), Runkel ratio (0.23-0.94), Rigidity coefficient (0.19-0.49), Flexibility coefficient (51.54-81.44), Slenderness ratio (31.68-62.74) and Luce's shape factor (0.20-0.58). All five species were determined to be appropriate for producing high-quality pulp and paper based on wood characteristics and fiber-derived indices grown in such hot and dry circumstances, but *Kadamb* fared best. The physical and anatomical characteristics of the wood were significantly impacted by tree height and GBH features. As a result, these attributes may be employed as indirect selection to further enhance the species that have shown high potentiality for promising pulpwood tree species under agroforestry. In order to meet the fastest-growing demand for pulpwood for India's paper industry, more study on tree development is needed to determine the best time to harvest for high pulp production and higher paper quality.

Keywords: Pulp and paper quality, pulpwood tree species, agroforestry, wood basic density, wood characteristics, and semi-arid zones.

Introduction

An essential raw resource for India's pulp and paper industry is pulpwood agroforestry tree species. Fast-growing tree species are planted in agroforestry plantations to meet India's pulpwood needs. The world's paper consumption is estimated to be 400 million tonnes, and it is expected to rise to 550 million tonnes by 2030. India's paper industry contributes around 3.0% of the world's paper output (IPMA 2022). The sustainable purchase of raw materials is a challenge for the Indian paper industry. In addition, timely delivery of high-quality materials from

agroforestry plantations was required. However, compared to the worldwide per capita use of 57 kg, India's per capita paper usage is a pitiful 13 kg. India is now seeing the fastest growth in paper consumption, with an annual growth rate of 6-7% (IPMA 2022). By 2025, the demand for pulp and paper is expected to rise by 24 million tonnes, while there will be a 12 million tonne pulpwood shortfall (Kulkarni 2013). Growing agroforestry plantations of fast-growing, short-rotation tree species is just one way to satisfy the increasing need for pulpwood; the pulp and paper industry's present demand cannot be met by the available wood supplies. Therefore, agroforestry plantations have a lot of potential to close the gap between India's pulpwood production and demand. The Bundelkhand area in central India has a semi-arid climate with an annual average of 35.1 °C and a hot, semi-humid rainfall of 760 mm. It consists of six districts in Madhya Pradesh (Datia, Tikamgarh, Chhatarpur, Panna, Damoh, and Sagar) and seven districts in Uttar Pradesh (Jhansi, Jalaun, Lalitpur, Mahoba, Hamirpur, Banda, and Chitrakoot). According to a recent research, the Bundelkhand area's yearly rainfall is trending downward, which suggests that the region is gradually drying up as a result of recurrent droughts and a lack of rainfall (Ahmed 2020). The development and productivity of agricultural crops in this semi-arid area are negatively impacted by this climate. Growing agroforestry tree species may boost vegetation, rainfall, and production while lowering losses from unfavourable climates. As a result, the rapidly expanding agroforestry tree species offer enormous potential for both permanent agriculture and meeting the increasing need for pulpwood. When choosing pulpwood for high-quality pulp and paper manufacturing, variability studies for the growth and wood characteristics of various agroforestry trees are crucial (Zobel & Van Buijtenen 1989). According to Dhaka and Jha (2017), Zobel and Talbert (1984), and Sharma et al. (2018), tree growth characteristics such as tree height, GBH (Girth at Breast Height), volume, and biomass are crucial for determining how well a tree species grows in various climates. According to Sinha et al. (2019), the Runkel ratio, flexibility coefficient, rigidity coefficient, slenderness ratio, and Luce's shape factor are derived from the wood's basic density and anatomical characteristics, including fibre length, fibre diameter, fibre lumen diameter, and fibre double cell wall thickness. Wood basic density, which was genetically regulated in trees (Zobel & Talbert 1984) and controls the strength and other physical characteristics of pulp and paper (Zobel & Van Buijtenen 1989), is a significant indication of fibre production and pulp output. While fundamental fines such vascular tissues, rays, and axial parenchyma elements reduce the paper bonding during sheet creation, wood fibre is the principal component of pulp. However, secondary fines that are formed during pulp refining improve the bonding of paper sheets (Sinha et al. 2019). Accordingly, the structure and mechanical strength of pulp and paper are influenced by fibre dimensions and the indices that are generated from them (Pirralho et al. 2014). As a result, differences in growth and wood characteristics including basic density, anatomical characteristics, and fibre indices are crucial markers for determining if a certain tree species is suitable for pulp and paper quality. Therefore, the current study was expanded with the following goals: (a) investigating the growth performance of five lesser-grown agroforestry tree species in the semi-arid zone; (b) assessing differences in the wood basic density, anatomical properties, and their derived indices among five lesser-grown agroforestry tree species in the semi-arid zone; (c) evaluating the suitability of these five lesser-grown agroforestry tree species in the semi-arid zone for the production of high-quality pulp and paper; and (d) using phenotypic correlation to examine the impact of growth attributes on the wood properties.

Materials and Methods

Five fast-growing, lesser-grown agroforestry trees—Maha Neem (*Ailanthus excelsa*), Safeda (*Eucalyptus tereticornis*), Subabul (*Leucaena leucocephala*), Malabar Neem (*Melia dubia*), and Kadamb (*Neolamarckia cadamba*)—were chosen at random from agroforestry plantations in and around Jhansi district (25°53'N latitude, 79°10'E longitude) in the Bundelkhand region (Uttar Pradesh), India). Five trees of each species were used to record the growth characteristics at a rotational age of two years. Using a Pressler Increment Borer, non-destructive core samples were obtained for the physical and anatomical characteristics of wood by coring at DBH (Diameter at Breast Height).

Tree Volume

Volume of tree was calculated using measured tree height and GBH as per the following equation (i) in cubic

meter.

$$\text{Tree volume (m}^3\text{)} = \frac{\text{GBH}^2}{4\pi} \times H \dots\dots\dots (i)$$

Where, H = Tree height (m), GBH = Girth at Breast Height (m), $\pi = 22/7$.

Tree Biomass

Tree biomass was calculated as suggested by Dhaka et al. (2020) using following equation (ii) in kilogram.

$$\text{Tree biomass (kg)} = \text{Tree volume (m}^3\text{)} \times \text{Wood basic density (kg/m}^3\text{)} \dots\dots\dots (ii)$$

Wood basic density

Wood basic density of wooden core samples was calculated as per Dhaka et al. (2020) using the following equation (iii) in gram per cubic centimeter.

$$\text{Basic density (g/cm}^3\text{)} = \frac{\text{Oven dry weight (g)}}{\text{Green volume (cm}^3\text{)}} \dots\dots\dots (iii)$$

Where, Oven dry weight = Dry weight of wood core samples after drying in a hot air oven (g),
Green volume = $\pi \times (D/2)^2 \times L$ (cm³)
{D = Diameter of wood core and L = Length of wood core}.

Measurement of fibre dimensions

The fibre parameters (length, diameter, lumen diameter, and double cell wall thickness) were measured using a small wood core sample, which was then subjected to Schultz's maceration method using 20 g of KClO₃ crystals and 5 ml of 50% HNO₃ (Jane 1956). Fibre diameter, lumen diameter, and double cell wall thickness were measured at 40× objective under a Leica trinocular microscope using LAS measurement software in accordance with International Association of Wood Anatomists committee guidelines (Wheeler et al. 1989). Fibre length was measured at least 25 randomly selected fibres at 4× objective. Fibre indices calculated from fibre dimensions

Five fibre derived indices were determined using the values of fibre dimensions commutated to assess the suitability of the tree raw materials for pulp and paper production as per Sinha et al. (2019).

(1) Runkel Ratio was calculated following equation (iv).

$$\text{Runkel ratio} = \frac{\text{Fibre double wall thickness } (\mu\text{m})}{\text{Fibre lumen diameter } (\mu\text{m})} \dots\dots\dots (iv)$$

(2) Rigidity coefficient was calculated following equation (v).

$$\text{Rigidity coefficient} = \frac{\text{Fibre double wall thickness } (\mu\text{m})}{\text{Fibre diameter } (\mu\text{m})} \dots\dots\dots (v)$$

(3) Flexibility coefficient was calculated following equation (vi).

$$\text{Flexibility coefficient} = \frac{\text{Fibre lumen diameter } (\mu\text{m})}{\text{Fibre diameter } (\mu\text{m})} \times 100 \dots\dots\dots (vi)$$

(4) Slenderness ratio was calculated following equation (vii).

$$\text{Slenderness ratio} = \frac{\text{Fibre length } (\mu\text{m})}{\text{Fibre diameter } (\mu\text{m})} \dots\dots\dots (vii)$$

(5) Luce's shape factor was calculated following equation (viii).

Luce's sape factor =

$$\frac{(Fibre\ diameter)^2 - (Fibre\ lumen\ diameter)^2}{(Fibre\ diameter)^2 + (Fibre\ lumen\ diameter)^2} \dots (viii)$$

Phenotypic Correlation:

Phenotypic correlation coefficients were calculated as following equation (ix).

Statistical analysis

All of the parameters that were measured and recorded in this study were statistically analysed using a randomised block design (RBD) with five replications. The statistical software package created by Sheoran et al. (1998) was used to construct an analysis of variance, and treatment means were compared at $P \leq 0.05$.

Results and Discussion Growth performance

Five lesser-grown agroforestry tree species were examined in the Jhansi district in the semi-arid zone of Bundelkhand, and growth characteristics such as tree height, GBH, tree volume, and tree biomass revealed a significant difference ($P \leq 0.05$) (Table 1). *Neolamarckia cadamba*, which generated a tree volume of 0.027 cubic meters with 15.28 kg biomass at the two-year rotation age, had the highest tree height (5.9 m) and GBH (24 cm).

$$r_{p(xy)} = \frac{Cov_{p(xy)}}{\sqrt{\sigma^2_{px} \times \sigma^2_{py}}} \dots (ix)$$

Where, $r_{p(xy)}$ = Phenotypic correlation

(Table 1). However, lowest tree height and GBH of *Ailanthus excelsa* attained 5.2 m and 20 cm which produced the tree volume 0.017 cubic meter and 8.50 kg biomass. Similarly, coefficient between character x and y,

$Cov_{p(xy)}$ = Phenotypic covariance for traits x and y respectively, σ^2_{px} = Phenotypic variance for traits x,

σ^2_{py} = Phenotypic variance for traits y. *Eucalyptus tereticornis*, *Leucaena leucocephala* and

Melia dubia attained good tree height (5.6, 5.8, 5.7 m) and GBH (20.8,

22.6, 20.4 cm) which produced 11.36, 12.92 and 9.59 kg biomass per tree in the comparable range (Table 1).

Table 1. Growth performances of five lesser-grown agroforestry tree species in the semi-arid zone

Pulpwood Species	Tree height (m)	GBH (cm)	Tree volume (m ³)	Tree biomass (kg)
<i>Ailanthus excelsa</i>	5.2±0.07	20.0±0.71	0.017±0.01	8.50±0.060
<i>Eucalyptus tereticornis</i>	5.6±0.05	20.8±0.49	0.019±0.01	11.36±0.48
<i>Leucaena leucocephala</i>	5.8±0.03	22.6±0.51	0.023±0.01	12.92±0.65
<i>Melia dubia</i>	5.7±0.05	20.4±0.51	0.019±0.01	9.59±0.56
<i>Neolamarckia cadamba</i>	5.9±0.04	24.0±0.71	0.027±0.01	15.28±1.09
Mean	5.64	21.56	0.021	11.53
SE(m)±	0.03	0.61	0.01	0.70
C.D.	0.10	1.85	0.01	2.10
CV (%)	1.36	6.33	13.16	13.48

For large-scale multiplication and planting programs in agroforestry, high-quality genotypes or clones are chosen based on growth metrics, productivity potential, and biomass (Dhaka et al. 2020). Important wood physical and anatomical characteristics as well as growth qualities are thoroughly researched for such rapidly expanding agroforestry species in various climatic conditions for paper and

pulp, as was subsequently mentioned. Twenty genotypes of *Neolamarckia cadamba* were measured for growth characteristics, including height, girth at breast height (GBH), and volume, at ages of one, two, three, four, and five years in order to assess the species' potential for growth at TNAU, Tamil Nadu (Parthiban et al. 2019). Kumar et al. (2013) found that the height, DBH, and volume of twenty open pollinated families of *M. dubia* at TNAU, Tamil Nadu varied significantly, ranging from 0.06 to 0.10 m³ at one year of age. Twenty-one progenies chosen from a single *Ailanthus excelsa* tree showed significant genetic heterogeneity in terms of field emergence, seedling height, shoot length, root length, basal diameter, and branch count (Daneva et al. 2018). Twenty genotypes of *Eucalyptus tereticornis* at two years old in Hoshiarpur, Punjab, showed notable differences in height (5.7–10.3 m) and DBH (3.76–6.69 cm), according to Kumar et al. (2010). Significant findings in the instance of *Leucaena leucocephala* demonstrated the impact of tree spacing on DBH development and tree height at harvesting ages of one and two years (Chotchutima et al. 2013). Growth habit, climatic and edaphic characteristics, tree age, genetic composition, and other silvicultural management techniques are some of the key aspects that influence a tree's growth and development (Khanna 2015). All five of these species performed better, according to the study's findings, however Kadamb is the most promising agroforestry pulpwood species.

Wood physical properties

The performance and strength quality of wood are influenced by its physical characteristics, such as its fundamental density and moisture content. Wood basic density is a crucial wood property that regulates pulp and paper's strength as well as a number of other physical attributes (Zobel and van Buijtenen 1989). The wood basic density of five distinct lesser-grown agroforestry species used for pulp and paper production differed greatly in the current research, ranging from 509.6 kg/m³ (*Melia dubia*) to 584.4 kg/m³ (*Eucalyptus tereticornis*) (Table 2).

Table 2. Wood basic density of five lesser-grown agroforestry tree species in the semi-arid zone

Pulpwood Species	Wood basic density (kg/m ³)
<i>Ailanthus excelsa</i>	511.2±1.77
<i>Eucalyptus tereticornis</i>	584.4±3.36
<i>Leucaena leucocephala</i>	546.6±5.00
<i>Melia dubia</i>	509.6±3.27
<i>N. cadamba</i>	559.8±4.66
Mean	542.30
SE(m) (±)	2.03
C.D.	6.14
CV (%)	0.84

In comparison to many other pulpwood species, the wood basic density of the five trees in our research is rather low (Parthiban and Sreenivasan 2017; Sinha et al. 2019). According to the present

research, the basic density of these five lesser-grown agroforestry tree species in the semi-arid zone is fairly low to medium, which is encouraging for the production of flexible paper sheets. Due to strong parental genetic control in nature, wood basic density can vary within a hole tree, between trees of the same species, between different species, and between geographical sources in different forest tree species (Zobel & Talbert 1984; Tripathi & Poonia 2015; Poonia & Tripathi 2016; Sihag et al. 2017). Climate-related variables may be the reason why the basic density in the current research was greater than in a damp area.

Wood anatomical properties

The most significant wood characteristics that affect pulp yield and paper-making qualities are fibre length, fibre diameter, fibre lumen diameter, and fibre double wall thickness (Zobel & van Buijtenen 1989; Sinha et al. 2019). The current research found that the fibre content of five lesser-grown agroforestry pulpwood species varied significantly.

characteristics viz., fibre length (914.4µm in *Eucalyptus tereticornis* to 1416 µm in *Neolamarckia cadamba*), fibre diameter (14.6 to 37.9 µm), fibre lumen diameter (7.5 to 29.8 µm), and fibre double wall thickness (4.8 to 9.7 µm) (Table 3). Although all these five species performed better for wood fibre characteristics.

Table 3. Fibre characteristics of five lesser-grown agroforestry tree species in the semi-arid zone

Pulpwood Species	Fibre length (µm)	Fibre diameter (µm)	Fibre lumen diameter (µm)	Fibre cell double wall thickness (µm)
<i>Ailanthus excelsa</i>	1208.8±9.88	21.7±0.30	16.1±0.09	5.6±0.21
<i>Eucalyptus tereticornis</i>	914.4±3.14	14.6±0.17	7.5±0.20	7.1±0.05
<i>Leucaena leucocephala</i>	932.6±2.84	20.8±0.23	11.1±0.13	9.7±0.10
<i>Melia dubia</i>	819.8±3.38	25.9±0.19	21.1±0.30	4.8±0.13
<i>N. cadamba</i>	1416.0±4.15	37.9±0.50	29.8±0.35	8.1±0.27
Mean	1058.32	24.17	17.12	7.05
SE(m) (±)	4.07	0.22	0.17	0.14
C.D.	12.30	0.67	0.52	0.43
CV (%)	0.86	2.05	2.25	4.55

Long fibres often boost pulp production and paper strength quality, whereas fibre diameter, lumen diameter, and cell wall thickness warn of fibre flexibility and coarseness (Sinha et al. 2019). Mohammed and Nasroun (2012) measured the average fibre length (1280 μm) at 12 places on ailanthus trees that represented three height levels and four radial locations at each height level with varying distances from the pith. At four and a half years of age, Sreevani and Rao (2014) examined the fibre properties of six clones of *Eucalyptus tereticornis* within the similar range (866-948 μm in fibre length; 12.54-13.08 μm in fibre diameter). *Leucaena leucocephala* had mean fibre length, diameter, lumen width, and cell wall thickness of 1200 μm , 21.56 μm , 10.79 μm , and 5.64 μm , respectively (Ogunjobi et al. 2018). Swaminathan et al. (2012) evaluated the differences in wood fibre properties between fast-grown and slow-grown *Melia dubia* trees. Fast-grown timber had higher values for anatomical properties such as fibre length (1055.5 μm), fibre diameter (37.5 μm), fibre lumen diameter (25.3 μm), and double wall thickness (12.2 μm) than slow-grown timber (914.5, 36.1, 24.3, and 11.8 μm , respectively). When Sinha et al. (2019) examined the wood anatomical variations of *M. dubia* at five different age gradations at NAU, Navsari, they discovered that, in comparison to other age gradations, five-year-old trees provided greater values for fibre length (1066.13 μm) and fibre wall thickness (2.59 μm). When Gujar et al. (2015) examined the wood anatomical characteristics of *Anthocephalus cadamba* at five different ages, they discovered that the fibre length (1509.13 μm), fibre diameter (40.53 μm), lumen diameter (29.27 μm), and cell wall thickness (5.53 μm) at two years of age were similar to those of other age groups. All five pulpwood species may be used to create flexible and robust paper sheets because longer fibres with thin cell walls will boost the paper sheet's flexibility and tensile strength.

Fibre derived indices

Table 4 displays the values (indices) determined from fibre dimensions. At two years of age, these produced indices revealed notable differences between five lesser-grown agroforestry tree species. The Runkel ratio, which should be less than 1.0 and is regarded as thin cell walled fibre that may be used as pulp, is helpful for the conformability and collapsibility of fibres and pulp production (Runkel 1949). All five species in the current research had Runkel ratios ranging from 0.23 (Malabar Neem) to 0.94 (Safeda). This supports the idea that these five species are suitable for producing high-quality paper because their fibres are more flexible and have extremely thin cell walls than those of other pulpwood species (Sinha et al. 2019). Paper strength is measured using the flexibility coefficient, which shows the paper's strong tensile and bursting strength (Pirralho et al. 2014). The flexibility coefficient for each of the five species in the current research ranged from 51.44 (Safeda) to 81.44 (Malabar Neem), indicating strong strength characteristics of the fibres used to make paper (Table 4). Among the five species, the stiffness coefficient varied from 0.19 to 0.49, which is less than 0.50, which is regarded as a desirable pulpwood species because it enhances the collapsibility of fibres. According to Sinha et al. (2019), the stiffness coefficient is a crucial indicator of the bending resistance of paper and the rigidity of the fibres used to make it. As a result, all five of the less common agroforestry tree species have the potential to be utilised to produce robust, flexible paper for writing and printing. The slenderness ratio, which should be more than 33 for pulp and paper manufacturing, is linked to pulp digestibility, ripping resistance, and folding endurance of paper sheets (Arya & Lohara 2016; Sinha et al. 2019). The slenderness ratio in this research varied from 31.68 to 62.74 (Table 4). It is similar to other pulpwood species. Low values

indicate a decreased resistance to beating in the production of paper. Luce's form factor is a helpful measure for testing the pulp's resistance to beating (Luce 1970). Luce's form factor was lower than that of other pulpwood species in the current research, ranging from 0.20 to 0.58 among five lesser-grown agroforestry species under semi-arid zone climatic circumstances (Sinha et al. 2019). According to suitability indexes, all five of these tree species were determined to be appropriate for pulp and paper production. These potential plants are suggested for large-scale agroforestry plantings, particularly in hot, dry, semi-arid areas of Bundelkhand.

Table 4. Fibre derived indices of five lesser-grown agroforestry tree species in the semi-arid zone

Pulpwood Species	Runkel Ratio	Rigidity Coefficient	Flexibility Coefficient	Slenderness Ratio	Luce's Shape Factor
<i>Ailanthus excelsa</i>	0.35±0.01	0.26±0.01	74.11±0.61	55.77±0.32	0.29±0.01
<i>Eucalyptus tereticornis</i>	0.94±0.03	0.49±0.01	51.54±0.81	62.74±0.50	0.58±0.01
<i>Leucaena leucocephala</i>	0.88±0.01	0.47±0.01	53.32±0.07	44.90±0.36	0.56±0.01
<i>Melia dubia</i>	0.23±0.01	0.19±0.01	81.44±0.62	31.68±0.11	0.20±0.01
<i>N. cadamba</i>	0.27±0.01	0.22±0.01	78.70±0.27	37.36±0.39	0.24±0.01
Mean	0.53	0.32	67.82	46.49	0.37
SE(m) (±)	0.02	0.01	0.54	0.27	0.01
C.D.	0.05	0.02	1.64	0.81	0.02
CV (%)	6.26	3.93	1.79	1.29	4.25

Phenotypic correlation matrix

Because selection for one or more characteristics may result in correlated responses for other characters owing to pleiotropic and linkage disequilibrium, the phenotypic correlation is often computed to identify the appropriateness of different characters for indirect selection (Namkoong et al. 1988). Using phenotypic data from all five tree species, the current research calculated the phenotypic correlation between different growth features and wood qualities. The results indicated that, with the exception of a few, all growth factors had a substantial link with the physical and anatomical aspects of wood (Table 5). Dhaka et al. (2020) shown that *Melia* tree height and diameter had a favourable impact on wood quality indices, including basic density, fibre length, and fibre content. As a result, the physical and anatomical characteristics of wood were favourably impacted by tree height and GBH features; hence, these attributes were used as indirect selection to further develop the species.

Table 5. Effect of growth attributes on wood properties of five lesser-grown agroforestry tree species in the semi-arid zone

Parameters	Basic density	Fibre length	Fibre diameter	Fibre lumen diameter	Fibre cell double wall thickness
Tree height	0.506**	0.035 ^{NS}	0.453*	0.316 ^{NS}	0.595**
GBH	0.405*	0.437*	0.559**	0.413*	0.625**
Tree volume	0.432*	0.410*	0.595**	0.445*	0.642**
Tree biomass	0.591**	0.404*	0.516**	0.355 ^{NS}	0.694**

Note: N= 25; NS= Non-significant; * Significant at 5 %; ** Significant at 1 %.

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