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Journal of Agriculture and Ecology

ISSN: 2456-9410

Volume: 13

Journal of Agriculture and Ecology (2022) 13: 150-159
http://doi.org/10.53911/JAE.2022.13115

Journal of Agriculture and Ecology, 2022, Vol. 13, 150-159
http://saaer.org.in

Research Article **Open Access**

Growth attributes and wood properties of lesser-grown agroforestry tree species in the semi-arid zone for quality pulp and paper production

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Article Info

Article history
Received: 15 June 2022
Accepted: 20 June 2022
Available online: 22 June 2022

Key Words: Agroforestry, wood basic density, wood properties, pulp and paper quality, pulpwood tree species, semi-arid zone.

Abstract

Growth traits, wood properties, fibre dimensions and fibre derived indices of five lesser-grown agroforestry tree species viz., *Ailanthus excelsa*, *Eucalyptus tereticornis*, *Leucaena leucocephala*, *Melia dubia* and *Neolamarckia cadamba* were studied to evaluate the suitability of these species for pulp and paper production in the semi-arid zone of Bundelkhand, India. The result showed that there was a significant variation for all the studied traits. 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 m^3), biomass (8.50-15.28 kg), wood basic density (509.6-584.4 kg/m^3), 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). Kadamb performed better, however all five species were found to be suitable for making good quality pulp and paper on the basis of wood properties and fibre derived indices grown in such hot and dry conditions. Tree height and GBH traits were positively influenced on the wood physical and anatomical properties, therefore these traits can be used as indirect selection for further improvement of the species which shown high potentiality for promising pulpwood tree species under agroforestry. Further, tree improvement research work required to test the suitable harvesting period for high pulp yield and better paper quality to fulfil the fastest growing demand of pulpwood for paper industries in India.

Preferred citation: Dhaka RK & Prajapati DR. 2022. Growth attributes and wood properties of lesser-grown agroforestry tree species in the semi-arid zone for quality pulp and paper production. *Journal of Agriculture and Ecology*, 13: 150-159; http://doi.org/10.53911/JAE.2022.13115

Introduction

Pulpwood agroforestry tree species is an important raw material for the pulp and paper industries in India. Agroforestry plantation of fast-growing tree species are grown to fulfil the demand of pulpwood in India. The paper demand in the world is about 400 million tonnes and projected to be increased 550 million tonnes by the year 2030, whereas paper industries of India contribute about 3.0 % paper production to the global market

(IPMA 2022). Indian paper industries facing problems related to procurement of raw materials on the sustainable basis. Besides that, the good quality material from agroforestry plantation needed to supply the material on timely. On the other hand, the per capita paper consumption of India is 13 kg which is very low against the global per capita of 57 kg. Now, the paper consumption in India is fastest growing at the rate of 6-7 % annually (IPMA 2022). The projected pulp and paper demand is to be increase 24 million tonnes by 2025 with a shortage of 12 million tonnes of pulpwood (Kulkarni 2013). To fulfill the growing demand of pulpwood, the growing of agroforestry plantations of short rotation fast growing trees species is only one solution, whereas the existing wood resources are insufficient to meet out the current demand of pulp and paper industry. Hence, there is a great scope and potentiality of agroforestry plantation to break the gap between demand and supply of pulpwood in India.

Bundelkhand region of central India falls under semi-arid climatic conditions having annual temperature (35.1 °C) and annual rainfall (760 mm) of hot and semi-humid zone. It comprises seven districts (Jhansi, Jalaun, Lalitpur, Mahoba, Hamirpur, Banda and Chitrakoot) of Uttar Pradesh and six districts (Datia, Tikamgarh, Chhatarpur, Panna, Damoh and Sagar) of Madhya Pradesh. In the recent study, the annual rainfall in the Bundelkhand region is following a declining trend which indicates a gradual drying up this region due to shortage of rainfall and frequent droughts (Ahmed 2020). This climatic situation adversely affects the growth and yield of agricultural crops in this semi-arid region. The growing of agroforestry tree species can reduce the losses due to adverse climate and improve the vegetation, rainfall as well as productivity. Therefore, the fast-growing agroforestry tree species have a great scope for the permanent agriculture as well as to fulfil the growing demand of pulpwood.

Variability studies for growth and wood properties of different agroforestry trees are very important in the selection of pulpwood for good quality of pulp and paper production (Zobel and Van Buijtenen 1989). The tree growth parameters such as tree height, GBH (Girth at Breast Height), volume and biomass are the important parameters to access the growth performance of any tree species in the different climatic conditions (Dhaka & Jha 2017; Zobel and Talbert 1984; Sharma et al. 2018). For pulp and paper quality, the wood basic density, wood anatomical properties, such as fibre length, fibre diameter, fibre lumen diameter and fibre double cell wall thickness and their derived indices viz., Runkel ratio, flexibility coefficient, rigidity coefficient, slenderness ratio and Luce's shape factor (Sinha et al. 2019). Wood basic density is an important indicator of fibre productivity and pulp yield which was genetically controlled parameter in trees (Zobel & Talbert 1984) and control the strength and other physical properties of pulp and paper (Zobel & Van Buijtenen 1989). Wood fibre is the main constituent of pulp, whereas primary fines such vessel tissues, rays and axial parenchyma elements are reducing the paper bonding during sheet formation. Nevertheless, secondary fines molded in refining of pulp which enhance bonding of paper sheet (Sinha et al. 2019). Thus, fibre dimensions and their derived indices are important parameters which influence the structure and mechanical strength of pulp and paper (Pirralho et al. 2014). Therefore, variation in growth and wood properties such as basic density, anatomical properties and fiber indices are important indicators to assess the suitability of any tree species for pulp and paper quality. Hence, the present study was extended with the objectives of (a) exploring the growth performance of five lesser-grown agroforestry tree species in the semi-arid zone, (b) evaluating variations in the wood basic density, anatomical properties and their derived indices among five lesser-grown agroforestry tree species in the semi-arid zone, (c) assessing the suitability these five lesser-grown agroforestry tree species in the semi-arid zone for good quality pulp and paper production, and (d) to study the effect of growth attributes on the wood properties using phenotypic correlation.

Materials and Methods

Total five fast growing lesser-grown agroforestry trees viz., Maha Neem (*Ailanthus excelsa*), Safeda (*Eucalyptus tereticornis*), Subabul (*Leucaena leucocephala*), Malabar Neem (*Melia dubia*), and Kadamb (*Neolamarckia cadamba*) were randomly selected from the agroforestry plantations located in and around Jhansi district 25°53'N latitude, 79°10'E longitude) of Budelkhand region (Uttar Pradesh), India. The growth parameters from five trees for each species were recorded at rotational age of 2 years. For physical and anatomical properties of wood, core samples by non-destructive method were collected using Pressler Increment Borer 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.

$$Tree\ volume\ (m^3) = \frac{GBH^2}{4\pi}\ x\ H \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (i)$$

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

Tree Biomass

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

$$Tree\ biomass\ (kg) = Tree\ volume\ (m^3)\ x\ Wood\ basic\ dendity\ (kg/m^3) \ldots\ldots\ldots \quad (ii)$$

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.

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

Where, Oven dry weight = Dry weight of wood core samples after drying in a hot air oven (g), Green volume = $\pi x\ (D/2)^2\ x\ L\ (cm^3)$ {D = Diameter of wood core and L = Length of wood core}.

Measurement of fibre dimensions

Small wood core sample used to determine the fibre dimensions (length, diameter, lumen diameter and double cell wall thickness) followed by Schultz's maceration process using 5 ml of 50% HNO_3 and 20 g crystals of $KClO_3$ (Jane 1956). Fibre length at least 25 randomly chosen fibreswas measured at 4× objective, while fibre diameter, lumen diameter and double cell wall thickness were measured at 40× objective under Leica trinocular microscope with LAS measurement software according to International Association of Wood Anatomists committee guidelines (Wheeler et al. 1989).

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).

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

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

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

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

$$Flexibility\ coefficient\ = \frac{Fibre\ lumen\ diameter\ (\mu m)}{Fibre\ diameter\ (\mu m)}\ x\ 100 \ldots\ldots\ldots \quad (vi)$$

(4) Slendernessratio was calculated following equation (vii).

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

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

$$Luce's\ shape\ factor\ = \frac{(Fibre\ diameter\ )^2-(Fibre\ lumen\ diameter\ )^2}{(Fibre\ diameter\ )^2+(Fibre\ lumen\ diameter\ )^2} \ldots (viii)$$

Phenotypic Correlation:

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

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

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

Statistical analysis

The data of all the recorded and calculated parameters in the present study were subjected to statistical analysis following randomized block design (RBD) with five replications and analysis of variance was constructed using the statistical software package developed by Sheoran et al. (1998) and treatment means were compared at $P \leq 0.05$.

Results and Discussion

Growth performance

Growth parameters such as tree heigh, GBH, tree volume and tree biomass showed that there was significant difference (P≤0.05) among five lesser-grown agroforestry tree species studied at Jhansi district in the semi-arid zone of Bundelkhand (Table 1). Highest tree height (5.9 m) and GBH (24 cm) were recorded in *Neolamarckia cadamba* which produced tree volume 0.027 cubic meter with 15.28 kg biomass at the two-year rotation age (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, *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)
Ailanthus excelsa	5.2±0.07	20.0±0.71	0.017±0.01	8.50±0.060
Eucalyptus tereticornis	5.6±0.05	20.8±0.49	0.019±0.01	11.36±0.48
Leucaena leucocephala	5.8±0.03	22.6±0.51	0.023±0.01	12.92±0.65
Melia dubia	5.7±0.05	20.4±0.51	0.019±0.01	9.59±0.56
Neolamarckia cadamba	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

The selection of good quality genotypes or clones based on growth parameters, productivity potential and biomass are used for large scale multiplication and plantation programme in agroforestry (Dhaka et al. 2020). For paper and pulp, important wood physical and anatomical properties along with growth traits are also well studied for such fast-growing agroforestry species in different climatic condition which was later discussed. The variability for growth parameters such as height, girth at breast height (GBH) and volume were recorded among twenty genotypes of *Neolamarckia cadamba* at one-, two-, three-, four- and five-year age to access the growth potentiality of the species at TNAU, Tamil Nadu (Parthiban et al. 2019). Kumar *et al.* (2013) recorded a significant variation among twenty open pollinated families of *M. dubia* at TNAU, Tamil Nadu for height, DBH and volume and it varied from 0.06 to 0.10 m^3 at the age of one year. Significant genetic variation among twenty-one progenies selected from plus tree of *Ailanthus excelsa* was observed for field emergence, seedling height, shoot length, root length, basal diameter and number of branches (Daneva et al. 2018). Kumar et al. (2010) found significant variations for height (5.7-10.3 m) and DBH (3.76 to 6.69 cm) among twenty genotypes of *Eucalyptus tereticornis* at two-year age at Hoshiarpur, Punjab. In case of *Leucaena leucocephala*, significant results showed that the effect tree spacing on tree height and DBH growth at one year and two-year age harvesting (Chotchutima et al. 2013). The growth and development of trees is mainly controlled by several factors including growth habit, climatic and edaphic features, age of tree, genetic constituent and other silvicultural management practices (Khanna 2015). Thus, results in the present study showed that all these five species performed better, however Kadamb is most promising agroforestry pulpwood species.

Wood physical properties

Physical properties of wood such as basic density and moisture content are affecting the wood performance and its strength quality. Wood basic density is very important wood properties that control the strength and several other physical characteristics of pulp and paper (Zobel and van Buijtenen 1989). In the present study, wood basic density significantly varied from 509.6 kg/m^3(*Melia dubia*) to 584.4 kg/m^3(*Eucalyptus tereticornis*) among five different lesser-grown agroforestry species for the purpose of pulp and paper production (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)
Ailanthus excelsa	511.2±1.77
Eucalyptus tereticornis	584.4±3.36
Leucaena leucocephala	546.6±5.00
Melia dubia	509.6±3.27
N. cadamba	559.8±4.66
Mean	542.30
SE(m) (±)	2.03
C.D.	6.14
CV (%)	0.84

The wood basic density of five tree in the present study is moderately low compared to many other pulpwood species (Parthiban and Sreenivasan 2017; Sinha et al. 2019). The current study showed that the basic density is moderately low to medium which is a good sign for the flexible paper sheet making from these five lessor-grown agroforestry tree species in the semi-arid zone. Wood basic density may vary within a whole tree, between trees of same species, between different species, between geographical sources in different forest tree species (Zobel & Talbert 1984; Tripathi & Poonia 2015; Poonia & Tripathi 2016; Sihag et al. 2017) due to strong parental genetic control in nature. The basic density in the present study was higher than moist locality may be due to climatic factors.

Wood anatomical properties

Wood anatomical parameters such as fibre length, fibre diameter, fibre lumen diameter and fibre double wall thickness are the most important wood properties that influence quality and quality of the pulp yield and paper making properties (Zobel and van Buijtenen 1989; Sinha et al. 2019). In the present study, significant variation among five lesser-grown agroforestry pulpwood species was recorded for fibre 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)
Ailanthus excelsa	1208.8±9.88	21.7±0.30	16.1±0.09	5.6±0.21
Eucalyptus tereticornis	914.4±3.14	14.6±0.17	7.5±0.20	7.1±0.05
Leucaena leucocephala	932.6±2.84	20.8±0.23	11.1±0.13	9.7±0.10
Melia dubia	819.8±3.38	25.9±0.19	21.1±0.30	4.8±0.13
N. cadamba	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

Pulp yield and paper strength quality is usually increased by long fibres, whereas, fibre flexibility and coarseness are alerted by fibre diameter, lumen diameter and cell wall thickness (Sinha et al. 2019). Mohammed and Nasroun (2012) recorded fibre length and fibre diameter from 12 locations on ailanthus trees representing three height levels and four radial locations at each height level with different distances from the pith with an average fibre length (1280 µm). Sreevani and Rao (2014) studied fibre characteristics among six clones of *Eucalyptus tereticornis* at the age of four and half year within the comparable rage (866-948 µm in fibre length; 12.54-13.08 µm in fibre diameter).The mean fibre length, fibre diameter, fibre lumen width and cell wall thickness were recorded 1200µm 21.56µm, 10.79µm and 5.64µm, respectively in *Leucaena leucocephala* (Ogunjobi et al. 2018).In case of *Melia dubia*, Swaminathan et al. (2012) assessed variation in wood fibre properties among fast grown and slow grown trees, whereas fast grown timber showed higher values for anatomical properties *viz.*, fibre length (1055.5 µm), fibre diameter (37.5 µm), fibre lumen diameter (25.3 µm), double wall thickness (12.2 µm) of fibre when compared to slow grown timber (914.5, 36.1, 24.3 and 11.8 µm, respectively). Sinha et al. (2019) investigated wood anatomical variations of *M. dubia* at five different age gradation at NAU, Navsari and found that five-year-old tree provide higher values for fibre length (1066.13 µm) and fibre wall thickness (2.59 µm) as compared to other age gradations. Gujar et al. (2015) studied wood anatomical properties of *Anthocephalus cadamba* at five different ages and found the fibre length (1509.13 µm), fibre diameter (40.53 µm), lumen diameter (29.27 µm) and cell wall thickness (5.53 µm) at the age of 2 years were comparable with different age classes. Subsequently, longer fiber with thin cell wall will be increased the flexibility and tensile strength of paper sheet, these all five pulpwood species can be utilized for making flexible and strong paper sheet.

Fibre derived indices

The values (indices) derived from fibre dimensions are presented in Table 4 and these derived indices shown significant variations among five lesser-grown agroforestry tree species at the age of two years. Runkel ratio is useful for conformability and collapsibility of fibres and pulp yield which should be less than 1.0, and considered as thin cell walled fibre, and are suitable for use as pulp (Runkel 1949). In the present study, the Runkel ratio of all five species ranged from 0.23(Malabar Neem) to 0.94 (Safeda). This advocates that the fibres of these five species are very thin cell walled and flexible in comparison to other pulpwood species, which confirmations the suitability of these five species for making good quality paper (Sinha et al. 2019). The flexibility coefficient is used to measure the paper strength which indicates the high tensile and bursting strength of the paper (Pirralho et al. 2014). In the present study, the flexibility coefficient among all the five species varied from 51.44 (Safeda) to 81.44 (Malabar Neem which shows high strength properties of fibres for making paper (Table 4). In case of rigidity coefficient, it ranged from 0.19 to 0.49among all the five species which was less than 0.50 as considered to be good pulpwood species because it increases the collapsibility of fibres. The rigidity coefficient is an important index for rigidity of fibres to form paper which indicates the bending resistance of paper (Sinha et al. 2019). Therefore, all the five lesser-grown agroforestry tree species could be employed as a promising species for making flexible and strong paper used for printing and writing. Slenderness ratio is associated with pulp digestibility, tearing resistance and folding endurance of paper sheet which should be more than 33 is considered good for pulp and paper production (Arya & Lohara 2016; Sinha et al. 2019). In the present study, the slenderness ratio ranged from 31.68 to 62.74 (Table 4). It more or less comparable with other pulpwood species. Luce’s shape factor useful index to test the beating resistance of pulp and low values indicates the reduced resistance to beating in paper making (Luce 1970). In the present study, Luce’s shape factor ranged from 0.20 to 0.58among five lesser-grown agroforestry species in semi-arid zone climatic conditions which was lower than other pulpwood species (Sinha et al. 2019). Thus overall, all these five tree species were found to be suitable for pulp and paper making on the basis of suitability indices. These promising species recommended for large scale plantations in agroforestry specifically such hot and dry semi-arid regions 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
Ailanthus excelsa	0.35±0.01	0.26±0.01	74.11±0.61	55.77±0.32	0.29±0.01
Eucalyptus tereticornis	0.94±0.03	0.49±0.01	51.54±0.81	62.74±0.50	0.58±0.01
Leucaena leucocephala	0.88±0.01	0.47±0.01	53.32±0.07	44.90±0.36	0.56±0.01
Melia dubia	0.23±0.01	0.19±0.01	81.44±0.62	31.68±0.11	0.20±0.01
N. cadamba	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

The phenotypic correlation is generally calculated to recognize the suitability of various characters for indirect selection because selection for one or more characters may result in correlated response for other characters due to pleiotropic and linkage disequilibrium (Namkoong et al. 1988). In the present study, phenotypic correlation for various growth to the wood characteristics was worked out using phenotypic data from all the five tree species and result showed that all the growth traits significantly correlated with wood physical and anatomical properties except few ones (Table 5). Dhaka et al. (2020) showed that wood quality parameters, viz. basic density, fibre length and fibre content, were positively influenced by the tree height and diameter of Melia trees. Thus, tree height and GBH traits were positively affect the wood physical and anatomical parameters, therefore these traits used as indirect selection for further tree improvement of 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 %.

Conclusion

The study showed that the growth performance and wood properties of five lesser-grown agroforestry tree species varied significantly with fibre derived indices for pulp and paper suitability in the semi-arid zone of Bundelkhand. These species exhibited high potentiality as raw material for pulp and paper industries due to fast growing in nature and production of good quality fibres in the adverse climatic and dry conditions.

Acknowledgements

The authors are thankful to College of Horticulture and Forestry, Rani Lakshmi Bai Central Agricultural University, Jhansi for carrying out this important research work on lesser-grown agroforestry tree species which are promising pulpwood species for pulp and paper in India.

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