Research Article

Comparative Study of Willow (*Salix tetrasperma*) Wood and Lachi (*Eucalyptus camaldulensis*) Hardwood Species for Pulp and Paper Manufacture, Grown in Khyber Pakhtunkhwa

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Abstract | Pulp and Paper sector has been expanding throughout the world because of increasing literacy rate and population, hence substantial request for pulp and paper raw material. To fulfill the eco-friendly sources demand and The longevity of their forthcoming industries necessitates an alternative supply from rapidly maturing tree species (Agro-forestry). The sources for the pulp and paper manufacturing sectors would be broaden by investigating the pulping capacities of underutilized humid-zone Broadleaf woods. The present work will be relying on the equitable woody fiber anatomical dimensions of two types that are Willow (*Salix tetrasperma*) and Lachi (*Eucalyptus camaldulensis*). The excellence of pulp and paper is directly linked to the fiber characteristics such as fiber wall thickness, fiber lumen diameter, and fiber length. Several wood characteristics associated with paper quality will be deduced from the fiber dimensions, encompassing parameters like the wall coverage ratio, aspect ratio, solidity factors, Luce's shape factors, flexibility coefficient, and runkel ratio. The primary aim is to contrast the fiber quality of the two dense wood species within themselves.

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Introduction

Around 3000 BC the modern paper we use today evolved from the ancient art of Egypt civilization who used papyrus tree as paper making material. These papers are not the same as we use today, the more expert way of making paper start from Chinese named T'sai Lun in 100 AD, who used bamboo and mulberry fiber. This paper making art is then started all over the world in beginning of 15th century (Rullifank *et al*., 2020).

As with time the global wealth increases, the paper demand will be doubled by 2050 (Lamberg *et al*., 2012) With this global demand, it urges continuous research to ensure consistent and green material sourcing to retain the pulp and paper manufacturing sectors operative. Discrepancies in the demand and availability of raw resources significantly impact the advancement of the pulp and paper sector (Ofosu *et al*., 2020). To ensure sustainable supply of raw resources for pulp and paper manufacturing sectors, it is needed to find the plantation of renowned and used wood species (Kulkarni, 2013).

The main source of pulp and paper manufacturing is trees (Hawes, 2018). Wood pulp is a premium quality fiber which encompasses a high strength but with a high cost. The green material supply for the pulp and paper Industry would be broaden by investigating the pulping capacities of underutilized tropics based deciduous wood (Anthonio and Antwi-Boasiako, 2017). For example, for making wrapping papers and rigid cardboards, *Brachystegia spiciformis* Benth. and *Pericopsis angolensis* (Baker) Meeuwen were assessed to possess favorable pulping properties and appropriate (Sangumbe *et al*., 2018). *Ricinodendron heudelotii* (Baill.) Pierre ex Heckel fiber characteristics remained analyzed by Ogunleye *et al*. (2017) who determinde the suitability of specie for paper production (Ogunleye *et al*., 2017). The fiber characteristics of *Ricinodendron heudelotii* (Baill.) Pierre ex Heckel were analyzed by Ogunleye *et al*. (2017) who concluded their suitability for papermakin (Ogunleye *et al*., 2017). So it is the need of the time to analyze the pulping characteristics of other plentiful and fewer used tropical Hardwood species to increase the raw material pool for Pulp and paper industry (Ferreira *et al*., 2019).

The alternative sources been developed, having low-cost production and new paper products, but having lower brightness, such as Packaging- the fattest growing sector of paper (Höller *et al*., 2021). Willow (*Salix* spp.) belongs to family Salicaceae. *S. alpina* is a low-growing shale bush, 2–15 cm tall. Young leaves are pubescent, adults are bare, only with cilia along the edge, re-versed, whole, brilliant, dark green from above, up to 2cm in length. Salix is classified into 3 sub categories, namely Salix, Vetrix and Chamaetia (Meikle, 1984, 1992; Skvortsov, 1999). The specie of the family Salicaceae, Salix, is the largest and prevalent genus with ca.320 species in all over the world.

The physiognomic properties data of timber is needed for encouraging its use in the pulp and paper Industry, because such properties effect the pulpability of wood. The fiber characteristics, anatomical property, mainly influence the paper manufacture potentiality of timber resource (Boadu *et al*., 2017). The properties of paper that are to be affected by fibers are tearing resistance, bursting and tensile strengths, and stretch (Kiaei *et al*., 2016). Higher tear resistance paper is usually manufactured by long fibers. Other fiber derived indices, which give information to better conclude the papermaking potential of wood, are Runkle ratio, Slenderness Ratio, coefficient of Rigidity, Flexibility Coefficient, Luce's Shape Factor and solids Factor (Ververis *et al*., 2004).

Materials and Methods

Study area

For the scope of this study, the timber trees of two species, named Willow (*Salix tetrasperma*) wood and Lachi (*Eucalyptus camaldulensis*), were obtained from Range Forest Garden, Pakistan Forest Institute, Peshawar.

Wood material sampling and processing

The random selection of selected wood species was carried out and sourced at 1.3 m Base Level. The harvested woods were debarked by (De-barker machine) and logs were obtained. Some samples were chipped into radial chips with the help of Staffi chipper Machine. Chips were prepared from each wood species were classified and N-3 fraction (1 inch in length and 3.2 mm in thickness).

For basic density

The basic density of the wood can be calculated by the given formula:

Density = (Oven dry weight)/ (Green Volume) (Yadav *et al*., 2022)

There are other methods as well for wood density determination, but the standard method is to divide the oven dry weight by green volume of the same wood.

Determination of the fiber morphology of willow (Salix tetrasperma) wood and lachi (Eucalyptus camaldulensis) wood species

For maceration in order to determine the fiber morphological characteristics, a small portion of wood of each specie ray-like wood slices were softened (pulpified) in Schulze's process (30-percent HNO_3 (Nitric Acid) and a Squeeze of $KClO_3$ (Potassium chlorate). Following this practice, each sample of log radial chips, measuring half the length of a matchstick, was taken in diverse trial tube. For getting fully separated fibers, the trial tubes were positioned to receive direct sunlight for a period of two-three days. The separated fibers stayed carefully washed to deacidify. The macerated fibers were dyed with Safranin Stain in addition to observe under the microscope (Nikkon 55 I Eclips) in wood anatomy Laboratory (Pakistan Forest Institute, Peshawar) (Gupta and Gupta, 2020).

For this macerated fiber, measurements of fiber morphological properties were determined which are tabulated in Table 1. The IAWA (IAWA Committee, 1989) was trailed for the terminologies that are written for the fiber microstructure description (IAWA Committee, 1989).

Microscopic images were captured of both the sections and macerated fibers with the Nikkon Eclipse-55i standard microscope (Anatomy Lab, Forest Product and Research Division, Pakistan Forest Institute) equipped with a Nikkon 4x0.1 camera.

Timber features impacting pulp and paper grades

The assessment of pulp quality involved the calculation of wood properties including Luce's shape factor, flexibility coefficient, slenderness ratio, solids factor, fiber coarseness, and wall coverage ratio.

Determination of the fiber indices of willow (Salix tetrasperma) wood and lachi (Eucalyptus camaldulensis) wood species

The fiber indices were calculated for the selected species that are Runkle Ratio, Slenderness Ratio, Coefficient of Rigidity, Flexibility Coefficient, Luce's Shape Factor and Solids Factor.

Results and Discussion

Basic density

The basic density of both species is maximum at Freeness (SR^0) 64 which is 1.41±0.06 (g/cm^3) for willow and 1.2 ± m0.073 (g/cm^3) for Eucalyptus. Among them, willow has the highest density (Table 3). Pulp properties are strictly connected to wood density such as beating resistance, tensile strength, bursting strength, folding strength, sheet density and pulp yield. The paper sheet produced form low density wood have low pulp yield and tearing strength but high sheet density, folding, tensile and bursting strengths (Santos *et al*., 2012; Takeuchi *et al*., 2016).

Wood fiber properties related to pulp and paper quality

As per results of Tables 3 and 4, there is substantial variances can be found in fiber morphology (dimensions) i.e., Runkle ratio, slenderness ratio, coefficient of rigidity, flexibility coefficient, Lune's shape factor, solid factor, wall coverage ratio, fiber coarseness and basic density, between the five authentic samples of each Willow (*Salix tetrasperma*) and Lachi (*Eucalyptus camaldulensis*) wood species used in this study.

Table 1: *Directory of evaluation equations of timber fiber properties associated to pulp and paper grade.*

S. No	Related to pulp and paper properties	Property	Formula	References
1	Pulp yield (+) and digestibility (-)	Runkle ratio	(FWTx2) / (FLD)	(ROH, 1949)
2	Tearing strength (+)	Slenderness ratio	(FL) / (FD)	(Ona *et al*., 2001)
3		Coefficient of rigidity	(FWT) / (FD)	(AC, 1964)
4	Tearing and tensile strength (+)	Flexibility coefficient	(FLD) / (FD)	(Malan and Gerischer, 1987)
5	Resistance to beating (+)	Lune's shape factor	$[(FD)^2 - (FLD)^2] / [(FD)^2 + (FLD)^2)]$	(Page, 1970)
6	Sheet density (-)	Solid factor	$[(FD)^2 - (FLD)^2] \times (FL)$	(Ona *et al*., 2001)
7	Bending resistance (-)	wall coverage ratio	(2*FWT)/FD	(AC, 1964)
8	Fiber coarseness		$(FD^2) - (FLD^2)$	

FL= Fiber length; FD= Fiber diameter; FLD= Fiber lumen diameter; FWT= Fiber wall thickness.

Table 3: *Densities of two species at different freeness.*

Specie	Density @ freeness (SR^o) 25	Density @ freeness (SR^o) 43	Density @ freeness (SR^o) 64
Willow (*Salix tetrasperma*)	1.08±0.05	1.31±0.06	1.41±0.06
Lachi (*Eucalyptus camaldulensis*)	0.88±0.015	0.99±0.063	1.2±0.073

Hence, the mean density of willow is greater on all Freeness (SR^o) i.e., 25, 43 and 64, then the eucalyptus specie.

Table 4: *Comparative analysis of fiber derived indicators of Willow (Salix tetrasperma) to Lachi (Eucalyptus camaldulensis) cellulose sources for papermaking.*

Species	Runkel ratio	Slenderness ratio	Coefficient of rigidity	Flexibility coefficient	Luce's shape factor	Solid factor	wall cover-age ratio	Fiber coarseness
Willow (*Salix tetrasperma*)	0.38	44.6	0.14	0.72	0.31	0.33	0.27	294.07
Lachi (*Eucalyptus camaldulensis*)	0.69	54.87	0.34	0.6	0.217	0.112	0.41	139.36

Table 5: *Fiber morphological characteristics of Willow (Salix tetrasperma) wood.*

Fiber characteristics	Lachi (*Eucalyptus camaldulensis*)				
	Average value	Standard deviation (±)	Upper limit	Lower limit	Co-effient of variation (%)
Fiber length (mm)	0.81	0.12	0.93	0.69	19.81
Fiber diameter (µ)	14.76	3.04	17.8	11.72	20.79
Fiber wall thickness (µ)	3.05	0.53	3.58	2.52	21.49
Fiber lumen width (µ)	8.86				

Table 6: *Fiber morphological characteristics of Willow (Salix tetrasperma) wood.*

Fiber characteristics	Willow (*Salix tetrasperma*)				
	Average value	Standard deviation (±)	Upper limit	Lower limit	Co-effient of variation (%)
Fiber length (mm)	1.11	0.22	1.33	0.89	19.81
Fiber diameter (µ)	24.89	5.17	30.06	19.72	20.79
Fiber wall thickness (µ)	3.42	0.73	4.15	2.69	21.49
Fiber lumen width (µ)	18.04				

Willow (*Salix tetrasperma*) has the longest fiber as compared to Lachi (*Eucalyptus camaldulensis*), clearly mentioned in the above give graph, Figure 1. But here is an anomaly in the wall thicknesses of their fibers. The fiber wall thickness of Willow (*Salix tetrasperma*) was also greater the that of (*Eucalyptus camaldulensis*), which can be seen in the given graph (Figure 1). For best grade paper, elongated fibers with slim walls are highly recommended for Pulp and Paper industries (Yadav *et al*., 2022).

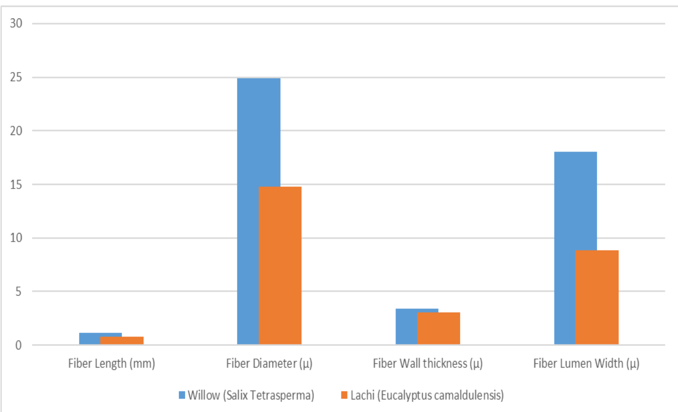

Figure 1: *Fiber cherecteristics comparison of Wilow and Lachi softwood species.*

In the paper manufacturing field, for high grade pulp and paper, the runkle ratio of fiber provides useful pulp yield or digestibility. The runkle ratio of Lachi (*Eucalyptus camaldulensis*), with average value 0.69, is greater that of Willow (*Salix tetrasperma*), with a value of 0.38.

The Runkel ratios given in the Table 4, gave high specific areas, which have required bonding ability. The Runkel ratio less than one, produced paper which will be comprises of excellent folding endurance, bursting and tensile strength, and will be compact and have smooth surfaces (Tutus *et al*., 2010). The tensile strength of the paper is directly related with the Runkle Ratio of the wood fibers (Oluwadare and Sotannde, 2007).

The fiber structural integrity (strength) enhances with the increase of slenderness ratio and fiber length (Shakhes *et al*., 2011). The mean value of Lachi (*Eucalyptus camaldulensis*) (54.87) is greater than Willow (*Salix tetrasperma*) (44.6). Therefore, the paper produced from Lachi (*Eucalyptus camaldulensis*) is responsible for its higher bursting and tensile strength as compare to Willow (*Salix tetrasperma*).

Luce's shape factor contributes for resistance to beating and flexibility coefficient for tearing and tensile strength of paper. Its value for Lachi (*Eucalyptus camaldulensis*) is 0.217 while for Willow (*Salix tetrasperma*) is 0.31. The paper strength produced was positively related to flexibility coefficient, burst and tear factors. Also, the flexibility coefficient value of Willow (*Salix tetrasperma*) is 0.72 and Lachi (*Eucalyptus camaldulensis*) is 0.6.

The solid factor was found directly related to the paper sheet density and the paper breaking length (Ona *et al*., 2001). But here in this study, solid factor value of Willow (*Salix tetrasperma*) is 0.33, higher than Lachi (*Eucalyptus camaldulensis*) which is 0.112.

The fabric material of wood is cellulosic elements that are extracted from trees, used for many different purposes which includes pulp and paper manufacturing (Oluwadare and Sotannde, 2007; San *et al*., 2016; Walker and Butterfield, 2006). PY (pulp yield), SD (sheet density), BF (burst factor) and BS (breaking strength) of paper are greatly influence by fiber dimensions such as fiber length, fiber lumen width etc. (Antwi-Boasiako and Boadu, 2016; Downes *et al*., 1997; Ek-Monica *et al*., 2009; Junior *et al*., 2009; Ona *et al*., 2001). There is a strong relation between the fiber length and the paper strength properties, higher the fiber length, higher will be the paper strength properties and vice versa (Marques *et al*., 2010; Syed *et al*., 2016). Hardwoods have small fiber length and consequently produce low strength papers as compare to softwoods which have long fibers (Ashori and Nourbakhsh, 2009; Oluwadare and Sotannde, 2007; Tutuş *et al*., 2015). The length of Willow (*Salix tetrasperma*) is 1.11±0.22 mm which is quite larger than Lachi (*Eucalyptus camaldulensis*) which is 0.81±0.12 mm, which makes the Willow (*Salix tetrasperma*) is important specie for pulp and paper production.

Paper sheet density could be determined by the fiber diameter. Paper with good sheet density could be produced from small diameter fibers (Sharma *et al*., 2015). The fiber with larger diameter increases pulp volume and their void spaces which subsequently produces a paper sheet with coarse-surface (Sharma *et al*., 2011; Syed *et al*., 2016). Papers with good sheet density can be produce from fibers which have fiber diameter ranges from 20–40 µm (Ates *et al*., 2008). The fiber diameter recorded for Willow (*Salix tetrasperma*) is 24.89 ± 5.17 µm while that of Lachi (*Eucalyptus camaldulensis*) is 14.76 ± 3.04 µm.

The potential of wood in paper manufacturing is allegedly affected by its fiber thickness and lumen diameter or lumen width. The wood fibers with thick walled are reportedly undesirable in paper manufacturing because they occupied large void volume, bulky and coarse surface (Raymond *et al*., 1998; Sharma *et al*., 2011).

The present study was carried on the two hardwood species namely Willow (*Salix tetrasperma*) and Lachi (*Eucalyptus camaldulensis*). These species were grown locally in the Research Range Garden of Pakistan Forest institute, Peshawar. This study will help the pulp and paper industry as well as the local community to grow the best specie on agro forestry basis. This study will help to reduce the pressure on traditional timber used in pulp and papermaking and encourage sustainable forestry practices and Agro-forestry in order to sustain nonstop timber resources for papermaking.

Conclusions and Recommendations

The current investigation was undertaken to compare the features of two well know species grown in Khyber Pakhtunkhwa used in pulp and paper production.

Willow (*Salix tetrasperma*) fiber dimensions such as FL (Fiber length), FD (Fiber diameter), FLD (Fiber lumen diameter) and FT (Fiber wall thickness) compared against Lachi (*Eucalyptus camaldulensis*), which are vastly used in the paper production. Fiber of the first mentioned specie is most suitable for pulp and paper industry and to be recommended for KPK local community to be grown as a Agro-Forestry specie. It is because the former specie has low fiber length as compare to the preceding specie. The base for the raw material to be used in the paper manufacturing can be increased by adding the both species i.e. Willow (*Salix tetrasperma*) and Lachi (*Eucalyptus camaldulensis*).

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Novelty Statement

This study provides a comparative analysis of Willow (*Salix tetrasperma*) and Lachi (*Eucalyptus camaldulensis*) grown in Khyber Pakhtunkhwa for pulp and paper production. It explores fiber quality, chemical composition, and pulp yield, offering insights into sustainable raw material sourcing and promoting eco-friendly practices in Pakistan's paper industry.

Author's Contribution

Abdur Rehman: Wrote original draft, resources, project administration, Methodology, Investigation, Formal analysis, Data curation.
Muhammad Umair khan: Contributed in Collection of data of review manuscript and composition of it. Handled the visualization of data and results.
Mansoor Ali Khan: Contributed in composition of review manuscripts and paraphrasing the literature data.
Abdur Rahman Khan: Writing – review & editing, software, Resources, Investigation, Data curation, Conceptualization.
Zahid Rauf: Contributed in collecting and tabulating the data and proof reading of review manuscript.
Saeed Akhtar: Contributed to the conceptualization of the study and the development of the research methodology. Also contributed to the critical review and editing of the manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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