

RESEARCH ARTICLE

PROSPECTS OF *ACROCARPUS FRAXINIFOLIUS* AS AN ALTERNATIVE RAW MATERIAL FOR THE PULP AND PAPER INDUSTRYVennila S^{1*}, S. Manivasakan² C. Cinthia Fernandez³ and S. Kala⁴¹Deptt. of Forestry, Agricultural College and Research Institute, TNAU, Tiruvanmalai - 606 753, Tamil Nadu²Deptt. of Forestry, ICAR KVK, TNAU, Ooty - 643002, Tamil Nadu³Deptt. of Agrl. Extension, Tamil Nadu Agricultural University, Coimbatore⁴ICAR-Indian Institute of Soil & water conservation Research Centre, Kota - 324 002, RajasthanEmail: vennila.s@tnau.ac.in

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Abstract: The growing demand for pulp and paper products has intensified the need to identify alternative and sustainable raw materials for the industry. *Acrocarpus fraxinifolius* Wight & Arn., a fast-growing multipurpose tree species native to tropical Asia, has gained attention for its potential as a pulpwood resource. The present study evaluates the prospects of *Acrocarpus fraxinifolius* as an alternative raw material for the pulp and paper industry by examining its physical and chemical characteristics. The results indicated that the species possesses moderate moisture content, satisfactory bulk and basic density, and a high proportion of acceptable chip fraction suitable for pulping operations. Chemical analysis revealed appreciable holocellulose content and comparatively lower lignin and extractives, which are favorable attributes for pulp production and paper quality. These characteristics are comparable with commonly used pulpwood species such as *Eucalyptus* and *Casuarina*. The findings suggest that *Acrocarpus fraxinifolius* can serve as a promising supplementary raw material for the pulp and paper industry. Its fast growth, adaptability to tropical conditions, and favorable wood properties further enhance its suitability for plantation-based pulpwood production. Adoption of this species could contribute to diversification of pulpwood resources and sustainable raw material supply for the paper industry.

Keywords: *Acrocarpus fraxinifolius*, Indigenous species, Pulp, Paper

INTRODUCTION

The pulp and paper industry is one of the major forest-based sectors worldwide, relying heavily on lignocellulosic raw materials for the production of paper, paperboard, and related products. Traditionally, the industry depends on a limited number of fast-growing tree species such as *Eucalyptus camaldulensis*, *Casuarina equisetifolia*, and *Populus deltoides* for pulp production due to their favorable fiber characteristics, rapid growth, and adaptability to plantation forestry. However, increasing demand for paper products, combined with pressure on natural forests and limited availability of conventional pulpwood species, has necessitated the exploration of alternative fast-growing tree species suitable for pulp and paper manufacturing.

In recent years, considerable attention has been given to identifying non-traditional species that can supplement the raw material requirements of the pulp and paper industry. Among these, *Acrocarpus fraxinifolius* has emerged as a promising multiutility tree species. This species, commonly known as pink cedar, is a fast-growing deciduous tree belonging to the family Fabaceae and is widely distributed in

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tropical and subtropical regions of Asia, including India, China, Myanmar, Indonesia, and Vietnam. The species is known for its rapid growth, straight bole and ability to adapt to a wide range of climatic and soil conditions, making it suitable for plantation forestry and agroforestry systems.

The wood of *A. fraxinifolius* is moderately dense and possesses desirable anatomical and chemical properties that may make it suitable for pulp and paper production. Fast growth rate, relatively short rotation period and good biomass yield further enhance its potential as an alternative pulpwood resource. In addition, the species is often cultivated for shade, timber and ornamental purposes, and its inclusion in agroforestry systems provides multiple ecological and economic benefits. Despite these advantages, systematic evaluation of its physical properties, fiber characteristics and pulping suitability remains limited.

With the increasing emphasis on sustainable raw material supply and efficient utilization of forest resources, assessing the suitability of new species for industrial applications has become essential. Therefore, the present study aims to evaluate the prospects of *Acrocarpus fraxinifolius* as an alternative raw material for the pulp and paper

industry by examining its key physical properties and chip characteristics in comparison with commonly used pulpwood species. The findings of this study are expected to provide useful insights into the potential utilization of this species in the pulp and paper sector and contribute to the diversification of raw material resources for sustainable industrial development.

MATERIALS AND METHODS

The investigations were carried out in the laboratory of Forest College and Research Institute, Mettupalayam., A billet of *Acrocarpus fraxinifolius* measuring one meter length and 50-60 cm girth was collected, debarked and chipped separately and screened. The screened chips were used for pulping experiments. Some chips were converted into dust for proximate chemical analysis. Based on the initial screening study in the laboratory, the wood samples were subjected to analysis of physical and chemical properties. The pulping experiments were also carried out to find out its suitability for papermaking.

Physical properties for pulpwood

The bulk density and basic density were determined using the displacement method (Haygreen and Bowyer, 1982). Moisture content of wood chips was determined after drying it at 100 ± 5 °C for 48 h. The billets collected across the age gradation were chipped in pilot chipper and air-dried for 24 hours. The wood chips were passed through different sieves (50 mm, 10 mm, 5 mm and 2 mm) as per TAPPI methods (TAPPI, 1980) for Chips classification.

Chemical properties for pulpwood

The billets of individual tree species were chipped in pilot chipper; air-dried and converted into wood meal in a laboratory pulp disintegrator. The wood dust of sample was prepared using Wiley mill and the wood dust passing through 40 mesh but retained over 60 mesh was subjected to analysis for moisture, ash, hot water soluble, one per cent NaOH soluble, AB extractive, Acid insoluble lignin, pentosans, hollocellulose as per TAPPI methods (TAPPI, 1980).

Strength properties for pulpwood

30 g (dry weight) pulp was taken and diluted to 1.5 per cent (w/v) with water. This pulp slurry was thoroughly mixed. It was further diluted to 1.0 per cent and kept for 30 min. The measured volume of this was transferred in the sheet form in order to make 60 gsm sheets. These hand sheets were prepared according to TAPPI standard T 205 om-88. By couching, the sheet was removed from the wire with the help of absorbent blotters. These sheets were pressed between the blotters at 0.27 mpa to increase the dryness and to consolidate the sheet and then these sheets were dried at 27 ± 1 °C and 65 per cent \pm 2 RH for 24 hrs. The dried sheets were air dried and were again conditioned at 27 ± 1 °C and 65 per cent \pm 2 RH for four hours before testing. The tensile strength, bursting strength, tensile energy absorption and elongation of paper

sheets were measured according to TAPPI standard T 494 om-88 (TAPPI, 1980).

RESULTS AND DISCUSSION

Physical properties of wood

The physical properties of wood, particularly basic density, bulk density, and moisture content, are very important in determining the quality and suitability of wood for various applications. Among these, moisture content plays a crucial role in influencing the performance of wood. Changes in moisture content directly affect the dimensional stability of wood, causing it to shrink or swell as it loses or absorbs moisture. Therefore, understanding the relationship between moisture content and dimensional stability is essential when utilizing forest products. Generally, wood that undergoes rapid moisture fluctuations is not preferred for practical applications because such changes can adversely affect its physical and mechanical properties, leading to deformation, cracking, or reduced strength.

Moisture Content

The moisture content of the different wood species analyzed ranged from 8.67% to 9.76%. Among the species studied, *Eucalyptus camaldulensis* recorded the highest moisture content (9.76%), indicating a relatively greater capacity to retain water compared to the other species. In contrast, *Casuarina equisetifolia* showed the lowest moisture content (8.67%), suggesting a comparatively drier wood composition. *Acrocarpus fraxinifolius* exhibited a moderate moisture content (8.9%), falling between the values observed for the other two species. The variation in moisture content among these species is important because moisture significantly influences the physical characteristics, dimensional stability, and mechanical performance of wood. Differences in moisture levels may affect the suitability of these species for various industrial applications such as timber, pulp, and other wood-based products, as wood with lower moisture content generally provides better stability and reduced shrinkage during processing and utilization (Haygreen and Bowyer, 1982; Tsoumis, 1991; Glass and Zelinka, 2010).

Bulk Density

The bulk density of the wood chips, measured on an oven-dry basis, exhibited a range from 191 to 270 kg m⁻³. Among the species analyzed, *Eucalyptus camaldulensis* demonstrated the highest bulk density at 270 kg m⁻³, suggesting that its wood chips are more compact and potentially denser than those of other species. In contrast, *Casuarina equisetifolia* recorded the lowest bulk density at 191 kg m⁻³, indicating a less compact structure. *Acrocarpus fraxinifolius* fell in between these two extremes, with a bulk density of 230 kg m⁻³, reflecting a moderate level of compactness in its wood chips. This variation in bulk density among the different species

highlights the importance of species selection in applications where wood chip density may influence performance and usability (Bajpai, 2018).

Basic density

The basic density measured on an oven-dry basis for both *Acrocarpus fraxinifolius* and *Eucalyptus camaldulensis* was found to be quite similar, with both species exhibiting a density of 510 kg m⁻³. In contrast, *Casuarina equisetifolia* demonstrated a notably lower basic density, recorded at 435 kg m⁻³. This variation in density among the species may have implications for their respective uses in various applications, such as construction and furniture making, where density can influence strength, durability, and overall performance of the wood (Haygreen and Bowyer, 1982; Tsoumis, 1991; Zobel and Van Buijtenen, 1989). Understanding these differences is crucial for selecting the appropriate species for specific purposes in forestry and wood industry practices.

Chips classification

The analysis of chip size distribution indicated no presence of oversized chips (>45 mm) among the species evaluated, demonstrating the efficiency of the chipping process and the suitability of the raw material for industrial pulping operations. Proper chip size distribution is essential in the pulp and paper industry because it ensures uniform cooking during the pulping process and improves fiber quality. In the present study, the majority of the chips produced were within the acceptable chip size fraction (>7 mm). Among the species examined, *Eucalyptus camaldulensis* recorded the highest proportion of acceptable chips (82.8%), followed by *Casuarina equisetifolia* with 81.5%, and *Acrocarpus fraxinifolius* with 80.5%. A higher proportion of acceptable chip size is desirable as it contributes to uniform chemical penetration and efficient pulping performance.

The proportion of pin chips (3–7 mm) ranged from 12.4% to 14.9%, with *Acrocarpus fraxinifolius* showing a slightly higher percentage compared to the other species. Pin chips are generally less desirable because they tend to overcook during the pulping process, potentially affecting pulp yield and fiber quality. However, the observed levels remain within acceptable limits for industrial operations. The dust fraction (<3 mm) was minimal across all species, ranging between 0.4% and 0.5%, indicating good chip quality and minimal material loss during processing. Excessive dust and fines are typically undesirable because they may lead to chemical overconsumption, reduced pulp quality, and operational inefficiencies in digesters.

Overall, the chip size distribution observed in the present study reflects an efficient chipping process and indicates that all three species can produce chips of suitable quality for pulping operations. Proper chip size distribution is widely recognized as a critical factor influencing digester efficiency, pulp

yield, and fiber quality, making it an important parameter in evaluating the suitability of wood species as raw materials for the pulp and paper industry (Bajpai, 2018; Gullichsen and Fogelholm, 2000; Sixta, 2019).

The assessment of three tree species highlights the strengths of each in terms of moisture content, density, and chip quality for industrial applications. *Acrocarpus fraxinifolius* is noted for its moderate moisture content and density, along with a commendable percentage of acceptable chips, making it a viable option for pulp and paper production. *Eucalyptus camaldulensis* is distinguished by its high bulk density and the greatest proportion of acceptable chip fraction, positioning it as particularly beneficial for industrial uses. Meanwhile, *Casuarina equisetifolia*, despite having a lower density, offers chip quality that is on par with the other species. Overall, all three species exhibit a strong potential for yielding over 80% acceptable chips and generating minimal dust, indicating their suitability as high-quality raw materials for industrial processing.

Chemical Properties of industrial wood species

The chemical composition of wood plays a crucial role in determining its suitability for industrial applications such as pulp and paper manufacturing, bioenergy production, and other wood-based industries. The major chemical constituents of wood include cellulose, hemicellulose (pentosans), lignin, and extractives, along with minor inorganic components represented by ash content. Variations in these components significantly influence pulping efficiency, fiber quality, and overall industrial utility (Haygreen J. G. and Jim L. Bowyer, 1982; D. Fengel and G. Wegener, 1989). The present study evaluated the chemical composition of three industrially important species *Acrocarpus fraxinifolius*, *Eucalyptus camaldulensis* and *Casuarina equisetifolia* to assess their potential for pulp and paper production.

Ash Content

Ash content is an indicator of the inorganic mineral content present in wood. High ash content may cause scaling problems in industrial processing and affect combustion efficiency. In the present study, ash content ranged from 0.38% to 0.65% among the species studied. *Acrocarpus fraxinifolius* recorded the highest ash content (0.65%), followed by *Eucalyptus camaldulensis* (0.46%) and *Casuarina equisetifolia* (0.38%). The relatively higher ash content in *Acrocarpus fraxinifolius* indicates a greater proportion of mineral elements in its wood. However, the values obtained in this study fall within the normal range for hardwood species (0.2–1.0%), indicating that all three species are suitable for industrial processing without major mineral-related issues. Similar ash content ranges in hardwoods have been reported by D. Fengel and G. Wegener (1989).

Acid Insoluble Lignin

Lignin is a complex phenolic polymer that provides rigidity and structural integrity to plant cell walls. In pulping industries, lignin must be removed to obtain pure cellulose fibers, and therefore species with lower lignin content are generally preferred. The acid-insoluble lignin content among the studied species ranged from 23.0% to 25.9%. Among the species analyzed, *Acrocarpus fraxinifolius* exhibited the highest lignin content (25.9%), closely followed by *Casuarina equisetifolia* (25.7%), while *Eucalyptus camaldulensis* recorded the lowest lignin percentage (23.0%). The lower lignin content observed in *Eucalyptus camaldulensis* suggests that it may require comparatively less chemical treatment during pulping, thereby improving pulping efficiency and reducing processing costs. These findings are consistent with earlier reports indicating that *Eucalyptus* species typically possess lower lignin content and are widely preferred in the pulp and paper industry (D. Fengel and G. Wegener, 1989).

Pentosans

Pentosans represent the hemicellulosic fraction of wood and play an important role in fiber bonding during paper formation. The pentosan content of the studied species ranged from 13.0% to 20.1%. *Acrocarpus fraxinifolius* showed the highest pentosan content (20.1%), followed by *Casuarina equisetifolia* (18.5%), whereas *Eucalyptus camaldulensis* recorded the lowest value (13.0%). Higher pentosan content contributes to improved paper strength properties, as hemicelluloses enhance fiber flexibility and bonding capacity. Therefore, the relatively high pentosan content observed in *Acrocarpus fraxinifolius* and *Casuarina equisetifolia* may contribute positively to paper strength characteristics.

Holo-cellulose

Holo-cellulose represents the total carbohydrate fraction of wood, consisting of cellulose and hemicellulose. High holo-cellulose content is desirable in pulpwood species since it indicates a greater proportion of fiber-forming components. In the present study, holo-cellulose content ranged from 70.7% to 74.8%. *Eucalyptus camaldulensis* exhibited the highest holo-cellulose content (74.8%), followed by *Casuarina equisetifolia* (71.6%), while *Acrocarpus fraxinifolius* recorded the lowest value (70.7%). The high holo-cellulose content observed in *Eucalyptus camaldulensis* indicates its superior suitability for pulp and paper production, as greater cellulose availability typically results in higher pulp yield and improved paper quality. Similar observations regarding the high cellulose content in *Eucalyptus* species have been documented in previous wood chemistry studies (Haygreen J. G. and Jim L. Bowyer, 1982).

Hot Water Solubility

Hot water solubility represents the proportion of low-molecular-weight carbohydrates, tannins, gums, and

other soluble substances present in wood. In this study, hot water solubility ranged from 3.20% to 3.6%. *Casuarina equisetifolia* exhibited the highest hot water solubility (3.6%), followed by *Eucalyptus camaldulensis* (3.4%) and *Acrocarpus fraxinifolius* (3.20%). Higher solubility values generally indicate the presence of a greater amount of water-soluble extractives and degraded carbohydrates, which may influence pulping behavior and chemical consumption during processing.

1% NaOH Solubility

The 1% sodium hydroxide solubility test is commonly used to estimate the amount of low-molecular-weight carbohydrates and degraded cellulose present in wood. In the present study, NaOH solubility ranged from 12.2% to 14.0%. *Casuarina equisetifolia* recorded the highest solubility (14.0%), followed by *Acrocarpus fraxinifolius* (13.6%) and *Eucalyptus camaldulensis* (12.2%). Higher NaOH solubility values may indicate the presence of degraded polysaccharides or higher extractive content, which could influence pulping performance and chemical consumption.

Alcohol-Benzene Extractives

Alcohol-benzene solubility represents the extractive components present in wood, including resins, waxes, fats, tannins, and phenolic compounds. These extractives can influence pulping efficiency, paper quality, and industrial processing. In the present study, extractive content ranged from 1.2% to 4.4%. Among the species studied, *Acrocarpus fraxinifolius* exhibited the highest extractive content (4.4%), while *Eucalyptus camaldulensis* (1.4%) and *Casuarina equisetifolia* (1.2%) recorded comparatively lower values. Higher extractive content may interfere with pulping processes and affect bleaching efficiency, whereas lower extractive levels are generally considered favorable for pulp production.

The comparative evaluation of the chemical composition of the three species indicates distinct advantages for industrial utilization. *Eucalyptus camaldulensis* exhibited higher holo-cellulose content and lower lignin concentration, making it particularly suitable for pulp and paper production due to improved cellulose yield and reduced chemical requirements during pulping. *Acrocarpus fraxinifolius* demonstrated higher lignin, pentosan, and extractive contents, indicating a greater presence of non-cellulosic components. While this may require more intensive pulping conditions, the higher hemicellulose content could contribute positively to paper strength properties. *Casuarina equisetifolia* showed moderate chemical composition values, suggesting a balanced profile suitable for pulpwood applications. Its chemical characteristics, combined with its rapid growth and adaptability to marginal soils, make it an important industrial species for plantation forestry.

Overall, the results indicate that all three species possess favorable chemical properties for pulp and

paper production, with *Eucalyptus camaldulensis* showing a slight advantage due to its higher cellulose content and lower lignin concentration. These findings support the potential use of these species as alternative pulpwood resources for sustainable industrial applications.

Pulp yield and kappa number

The kraft pulping characteristics of the selected wood species revealed noticeable differences in chemical requirement, pulp yield, and delignification efficiency. The chemical charge, expressed as Na₂O percentage, ranged from 15% to 17% among the species studied. *Eucalyptus camaldulensis* required the highest chemical charge (17%), followed by *Acrocarpus fraxinifolius* (16%), whereas *Casuarina equisetifolia* required the lowest charge (15%). The variation in alkali requirement may be associated with differences in lignin and extractive contents, which influence chemical consumption during the delignification process. Similar variations in chemical charge among hardwood pulpwood species have been reported in recent studies evaluating alternative raw materials for the pulp and paper industry (Bajpai, 2018; Hubbe *et al.*, 2020).

The unbleached pulp yield ranged from 42.84% to 48.50%. Among the species, *Casuarina equisetifolia* recorded the highest pulp yield (48.50%), followed by *Eucalyptus camaldulensis* (47.80%), while *Acrocarpus fraxinifolius* showed the lowest yield (42.84%). The comparatively higher pulp yield observed in *Casuarina equisetifolia* may be attributed to its favourable cellulose and hemicellulose composition and efficient carbohydrate retention during pulping. In contrast, the relatively lower yield of *Acrocarpus fraxinifolius* may be due to the dissolution of carbohydrates or differences in wood chemical composition. However, the yield obtained for *Acrocarpus fraxinifolius* still falls within the typical range reported for hardwood kraft pulping processes (Bajpai, 2018; Sixta, 2019).

The percentage of screen rejects was very low across all species, ranging from 0.42% to 0.52%, indicating efficient pulping and effective fiber liberation. *Eucalyptus camaldulensis* exhibited the lowest screen rejects (0.42%), while *Casuarina equisetifolia* recorded slightly higher rejects (0.52%). Low reject levels generally indicate uniform chip impregnation and adequate chemical penetration during cooking. The screened pulp yield ranged from 42.40% to 47.98%. *Casuarina equisetifolia* again showed the highest screened yield (47.98%), followed by *Eucalyptus camaldulensis* (47.38%), whereas *Acrocarpus fraxinifolius* recorded the lowest screened yield (42.40%).

The kappa number, which represents the residual lignin content remaining in the pulp after cooking, ranged from 17.5 to 21.4. Among the species, *Casuarina equisetifolia* exhibited the lowest kappa number (17.5), indicating more effective delignification during pulping. Conversely,

Acrocarpus fraxinifolius showed the highest kappa number (21.4), suggesting comparatively higher residual lignin content. However, these values fall within the acceptable range typically observed for hardwood kraft pulps, where kappa numbers between 15 and 25 are commonly reported (Hubbe *et al.*, 2020; Sixta, 2019).

The characteristics of black liquor further provide insights into the pulping efficiency and chemical utilization. The pH values ranged from 11.96 to 12.90, reflecting the strongly alkaline conditions characteristic of the kraft pulping process. *Eucalyptus camaldulensis* exhibited the highest pH value (12.90). Total solids content ranged from 224 to 231 g L⁻¹, with *Acrocarpus fraxinifolius* showing the highest value (231 g L⁻¹). The total titratable alkali (TTA) values ranged from 30.10 to 31.87, again with *Acrocarpus fraxinifolius* recording the highest value (31.87). Residual active alkali (RAA) varied from 3.72 to 8.90, with *Casuarina equisetifolia* showing the highest residual alkali (8.90), suggesting comparatively lower alkali consumption during the cooking process. Such variations in black liquor properties are commonly observed among different hardwood species and provide useful indicators of chemical consumption and pulping efficiency (Bajpai, 2018).

Overall, *Casuarina equisetifolia* demonstrated superior pulping performance with the highest pulp yield and lowest kappa number, indicating efficient delignification. *Eucalyptus camaldulensis* also exhibited favourable pulping characteristics, including high screened yield and minimal screen rejects. Although *Acrocarpus fraxinifolius* produced a slightly lower pulp yield and a higher kappa number, its performance remained within acceptable limits for hardwood pulping. Considering its satisfactory pulping characteristics, rapid growth, and adaptability to tropical conditions, *Acrocarpus fraxinifolius* can be considered a promising alternative raw material for the pulp and paper industry. The inclusion of such fast-growing species in plantation programmes could contribute to diversifying pulpwood resources and ensuring a sustainable supply of raw materials for the paper sector.

Strength properties of *Acrocarpus fraxinifolius*

The strength properties of paper pulp derived from the studied species showed considerable variation, reflecting differences in fiber morphology and bonding characteristics. Among the mechanical properties evaluated, the tensile index, breaking length, tear index, and burst properties provide important insights into the suitability of pulp for papermaking applications. The tensile index, which is a key indicator of the tensile strength of paper and the bonding ability between fibers, ranged from 24.09 to 50.00 Nm g⁻¹ among the species studied. *Eucalyptus camaldulensis* recorded the highest

tensile index (50.00 Nm g^{-1}), indicating superior fiber bonding and strength characteristics. This may be attributed to its favorable fiber dimensions and high cellulose content, which contribute to stronger inter-fiber bonding during sheet formation. *Casuarina equisetifolia* also showed good performance with a tensile index of 43.5 Nm g^{-1} . In contrast, *Acrocarpus fraxinifolius* recorded a considerably lower tensile index of 24.09 Nm g^{-1} , suggesting comparatively weaker fiber bonding. However, such values are still within the range reported for several hardwood pulps used in paper manufacturing (Bajpai, 2018; Hubbe *et al.*, 2020). Breaking length, another important parameter representing the maximum length of a strip of paper that can support its own weight before breaking, varied from 2421 to 5100 m among the species. *Eucalyptus camaldulensis* exhibited the highest breaking length (5100 m), reflecting its superior fiber strength and bonding characteristics. *Casuarina equisetifolia* showed a moderate breaking length of 2800 m, while *Acrocarpus fraxinifolius* recorded the lowest value (2421 m). The relatively lower breaking length observed in *Acrocarpus fraxinifolius* may be associated with differences in fiber length, cell wall thickness, and fiber flexibility, which influence the formation of strong fiber networks in paper sheets (Sixta, 2019).

The tear index, which represents the resistance of paper to tearing and is largely influenced by fiber length and fiber strength, ranged from 3.9 to 4.7 $\text{mNm}^2 \text{ g}^{-1}$. Among the species, *Casuarina equisetifolia* recorded the highest tear index ($4.7 \text{ mNm}^2 \text{ g}^{-1}$), indicating better resistance to tearing. *Eucalyptus camaldulensis* followed with a value of $4.10 \text{ mNm}^2 \text{ g}^{-1}$, while *Acrocarpus fraxinifolius* recorded the lowest tear index ($3.9 \text{ mNm}^2 \text{ g}^{-1}$). The comparatively higher tear resistance in *Casuarina equisetifolia* may be attributed to favorable fiber morphology and fiber strength, which enhance resistance to crack propagation in paper sheets (Hubbe *et al.*, 2020).

Similarly, the burst index and burst factor, which reflect the ability of paper to withstand pressure applied perpendicular to its surface, ranged from 1.5 to 2.7 $\text{kPa m}^2 \text{ g}^{-1}$ and 15 to 27.5, respectively. Among the species, *Eucalyptus camaldulensis* again demonstrated superior performance, recording the highest burst index ($2.70 \text{ kPa m}^2 \text{ g}^{-1}$) and burst factor (27.5). These values indicate strong fiber bonding and high sheet strength. *Casuarina equisetifolia* showed moderate burst strength, whereas *Acrocarpus fraxinifolius* recorded comparatively lower values. Burst strength is closely related to fiber bonding capacity and sheet formation quality, which tend to be higher in pulps with favorable fiber flexibility and cellulose content (Bajpai, 2018).

Overall, the results indicate that *Eucalyptus camaldulensis* possesses superior strength properties in terms of tensile, burst, and breaking length, making it highly suitable for high-strength paper products. *Casuarina equisetifolia* also exhibited satisfactory mechanical properties, particularly with respect to tear resistance. Although *Acrocarpus fraxinifolius* demonstrated comparatively lower strength properties, its values remain within acceptable ranges for certain grades of paper. Therefore, when blended with other pulpwood species or used for specific paper products, *Acrocarpus fraxinifolius* can still serve as a viable supplementary raw material for the pulp and paper industry.

CONCLUSION

The present study evaluated the potential of *Acrocarpus fraxinifolius* as an alternative raw material for the pulp and paper industry in comparison with *Eucalyptus camaldulensis* and *Casuarina equisetifolia*. The results demonstrated that although *Eucalyptus camaldulensis* and *Casuarina equisetifolia* exhibited comparatively superior pulping performance and paper strength properties, *Acrocarpus fraxinifolius* also showed acceptable characteristics for pulp production. In the kraft pulping process, *Acrocarpus fraxinifolius* required a moderate chemical charge and produced an unbleached pulp yield within the acceptable range for hardwood species, although slightly lower than the other two species. The screened yield and low percentage of screen rejects indicated efficient pulping and satisfactory fiber separation. The kappa number values suggested that the species underwent adequate delignification, even though the residual lignin content was slightly higher compared to the other species studied. The properties of black liquor, including pH, total solids, and alkali parameters, further confirmed that the pulping process proceeded under suitable alkaline conditions.

The evaluation of paper strength properties revealed that *Acrocarpus fraxinifolius* exhibited lower tensile index, breaking length, tear index, and burst strength compared with *Eucalyptus camaldulensis* and *Casuarina equisetifolia*. However, the observed values remained within acceptable limits for several grades of paper, particularly when the pulp is blended with stronger fibers. These results indicate that although the species may not match the mechanical strength of conventional pulpwood species, it can still contribute effectively as a supplementary raw material.

Considering its fast growth, adaptability to tropical conditions, and satisfactory pulping characteristics, *Acrocarpus fraxinifolius* shows considerable promise

as an alternative pulpwood species. The incorporation of this species into plantation programs could help diversify the raw material base of the pulp and paper industry and reduce dependence on traditional species. Further studies on fiber

morphology, pulping optimization, and large-scale plantation performance would strengthen its potential for commercial utilization in pulp and paper production.

Table 1. Physical characteristics of *Acrocarpus fraxinifolius*

Sl. No.	Physical properties	<i>Acrocarpus fraxinifolius</i>	<i>Eucalyptus camaldulensis</i>	<i>Casuarina equisetifolia</i>
1.	Moisture Content (%)	8.9	9.76	8.67
2.	Bulk density (OD basis) (kg /m ³)	230	270	191
3.	Basic density (OD basis) (kg /m ³)	510	510	435
4.	Chips Classification			
	+ 45 mm	Nil	Nil	Nil
	+ 8mm (over thick)	4.2	4.4	5.4
	+ 7 mm (accepts)	80.5	82.8	81.5
	+ 3 mm (pin chips)	14.9	12.4	12.6
	- 3mm (dust)	0.4	0.4	0.5

Table 2. Proximate Chemical Composition of *Acrocarpus fraxinifolius*

Sl. No.	Chemical properties	<i>Acrocarpus fraxinifolius</i>	<i>Eucalyptus camaldulensis</i>	<i>Casuarina equisetifolia</i>
1.	Ash content (%)	0.65	0.46	0.38
2.	Acid insoluble lignin (%)	25.9	23.0	25.7
3.	Pentosans (%)	20.1	13.0	18.5
4.	Hollo cellulose (%)	70.7	74.8	71.6
5.	Hot water Solubility (%)	3.20	3.4	3.6
6.	1% NaOH Solubility (%)	13.6	12.2	14.0
7.	Alcohol benzene Solubility (%)	4.4	1.4	1.2

Table 3. Pulping results of *Acrocarpus fraxinifolius*

Sl. No.	Pulping properties	<i>Acrocarpus fraxinifolius</i>	<i>Eucalyptus camaldulensis</i>	<i>Casuarina equisetifolia</i>
1.	Chemical charge as Na ₂ O (%)	16	17	15
2.	Unbleached pulp yield (%)	42.84	47.80	48.5
3.	Screen rejects (%)	0.44	0.42	0.52
4.	Screened yield (%)	42.4	47.38	47.98
5.	Kappa number	21.4	20.48	17.5
	Black liquor			
6.	pH	11.96	12.90	12.7
7.	Total solid (gpl)	231	224	227
8.	TTA* as Na ₂ O	31.87	31.70	30.10
9.	RAA* as Na ₂ O	3.72	4.60	8.9

Cooking conditions
gpl total solids basis
Temperature : 170°C
Time : 90 min.

* TTA and RAA as Na₂O are calculated at 200

Table 4. Strength Properties of *Acrocarpus fraxinifolius*

Sl.No	Strength Properties	<i>Acrocarpus fraxinifolius</i>	<i>Eucalyptus camaldulensis</i>	<i>Casuarina equisetifolia</i>
1.	Tensile index (Nm/g)	24.09	50.00	43.5
2.	Breaking length (M)	2421	5100	2800
3.	Tear index (mNm ² /g)	3.9	4.10	4.7
4.	Tear Factor	39.82	41.8	47
5.	Burst index (kPam ² /g)	2.0	2.70	1.5
6.	Burst Factor	20.50	27.5	15

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