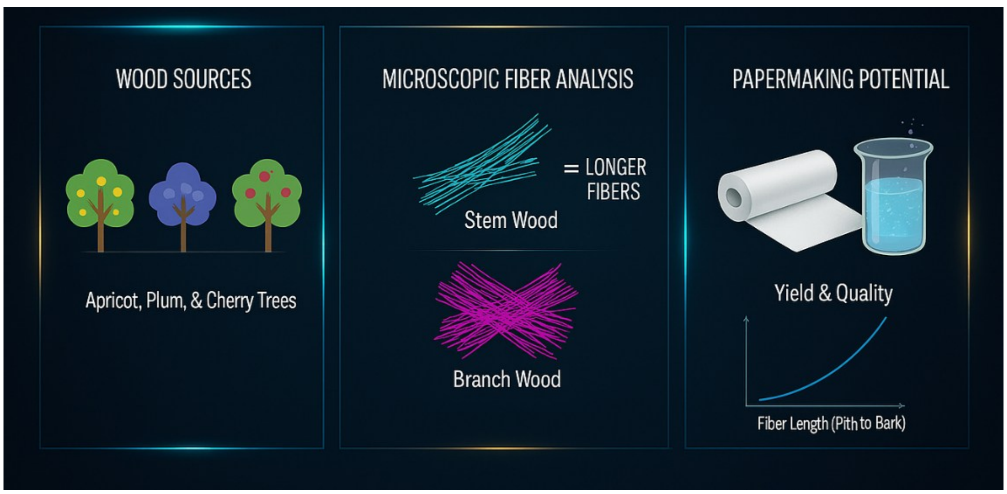
Comparative Analysis of Stem and Branch Biometrics in Wood Samples from Apricot, Plum, and Cherry for Papermaking Applications

Milad Tajik,[a,*] Hossein Kermanian,[b] Esmaeil Rasooly Garmaroody,[b] and Omid Ramezani,[b]

* Corresponding author: milad.tajik67@yahoo.com

DOI: 10.15376/biores.21.2.3158-3168

GRAPHICAL ABSTRACT



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This study evaluated and compared the biometric properties of wood from three fruit tree species: apricot, plum, and cherry. Three healthy trees from each species were randomly selected and sampled from gardens in Shahriyar, Tehran Province, Iran. Biometric analysis was conducted on fiber samples taken from radial positions at 25%, 50%, 75%, and 90% of the stem and branch radius. The Franklin method was used for fiber separation, and 30 fiber dimensions were measured per sample. The maximum fiber length was observed in apricot stem wood at 50% radius (1282 µm), and the minimum in apricot branch wood at 25% radius (835 µm). Across all three species, stem wood showed higher values for fiber length, slenderness coefficient, Runkel ratio, and rigidity ratio compared to branch wood. These properties generally increased from pith to bark, and the variations were statistically significant at the 99% confidence level.

DOI: 10.15376/biores.21.2.3158-3168

Keywords: Biometrics; Apricot wood; Plum wood; Cherry wood; Papermaking; Stem; Branch

Contact information: a: Department of Wood and Paper Science & Technology, Faculty of Natural Resources, University of Tehran, Tehran, Iran; b: Department of Bio Refinery, Faculty of New Technologies Engineering, Shahid Beheshti University, Tehran, Iran;
** Corresponding author: milad.tajik67@yahoo.com*

INTRODUCTION

In recent decades, the increasing global demand for lignocellulosic materials, coupled with rising limitations on timber harvesting and stricter environmental regulations, has intensified interest in non-wood and agricultural biomass as sustainable alternatives for pulp and paper production. In countries with limited forest resources—such as Iran—identifying reliable, renewable, and technically suitable raw materials has become increasingly important (Harry 1995; Karimi and Osare 2003; Abdul Khalil *et al*. 2006; Karimi *et al.* 2007; Parsapajouh and Schweingruber 2008)

Iran possesses one of the world's largest cultivated areas of fruit trees, with more than 6.2 million hectares—almost half of the country's agricultural land—under fruit tree cultivation. Each year, approximately 35 million fruit seedlings are produced to replace senescent or low-yielding trees, generating substantial volumes of woody residues that are typically underutilized (Harry 1995; Karimi and Osare 2003; Karimi *et al.* 2007; Parsapajouh and Schweingruber 2008; Andze *et al.* 2024). Apricot (*Prunus armeniaca* L.), plum (*Prunus domestica* L.), and cherry (*Prunus avium* L.) are among the most widely cultivated fruit species in Iran, with cultivation areas of approximately 63,958, 38,547, and 33,426 hectares, respectively. Iran ranks as the second-largest producer of apricots, the third-largest producer of cherries, and the fifth-largest producer of plums globally (Kiaei *et al.* 2014; Tajik *et al.* 2015; Guo *et al.* 2022; Andze *et al.* 2024).

The anatomical and wood-quality properties of these fruit species have been reported to vary considerably between stem and branch wood due to differences in mechanical loading, growth stresses, and cambial activity. Branch wood often exhibits shorter fibers, higher microfibril angles, and differences in wall thickness or lumen dimensions, all of which influence its suitability for papermaking (Guo et al. 2022; Bahmani *et al.* 2021). Several studies have investigated these variations: Hassan *et al.* (2020) reported comparable differences in stem and branch properties of *Eucalyptus camaldulensis* and *Pinus halepensis* for papermaking; Guo *et al.* (2022) examined fiber morphology in walnut branchwood, noting its suitability for papermaking with minimal influence from branch diameter, branching level, or tension wood. Andze *et al.* (2024) characterized cocoa branch wood, showing promising kraft pulp properties with high mechanical strength compared to traditional hardwoods. Bahmani *et al.* (2021) studied fiber morphology and physical properties in hawthorn stem and branch wood, noting altitude effects on density and fiber length. Mahdavi *et al.* (2010) compared mechanical properties of date palm fiber-polyethylene composites from trunk, rachis, and petiole, highlighting variations in fiber length and chemical composition, and Tırak Hızal and Birtürk (2024) analyzed biometric coefficients of woody plants under varying ecological conditions, confirming their potential for papermaking despite regional differences.

Despite the abundance of fruit tree residues in Iran, systematic and comparative studies on the biometric characteristics of stem and branch wood of apricot, plum, and cherry—especially regarding their papermaking potential—remain limited. Recent research highlights that stem wood fibers typically provide higher bonding potential and strength, while branch wood may enhance drainage or refining efficiency, suggesting that optimized blending strategies could be advantageous (Hassan *et al.* 2020; Guo *et al.* 2022; Andze *et al.* 2024; Tırak Hızal and Birtürk 2024). Therefore, the objective of this study was to compare the biometric properties of stem and branch wood from apricot, plum, and cherry trees and to assess their potential suitability for pulp and papermaking applications.

EXPERIMENTAL

Materials

Three healthy trees of each species—apricot (*Prunus armeniaca*), plum (*Prunus domestica*), and cherry (*Prunus avium*)—were randomly selected and harvested from orchards in Shahriyar, Tehran Province, Iran (latitude 35.39° N, longitude 51.03° E). From each tree, two discs were cut: one from the stem at breast height and another from a representative branch. To avoid the influence of reaction (tension) wood, branch discs were collected from the lower and neutral sides of the branch at a height of approximately 30 to 40 cm from the branch base, ensuring that the upper tension-wood zone was not included in sampling (Guo *et al.* 2022; Andze *et al.* (2024).

The trees were approximately 10 years old, with an average stem diameter of 25 cm and branch diameter of 10 cm. Thin wood chips were extracted from four radial positions within each disc: 25% (near the pith), 50%, 75%, and 90% (near the bark), as illustrated in Fig. 1.

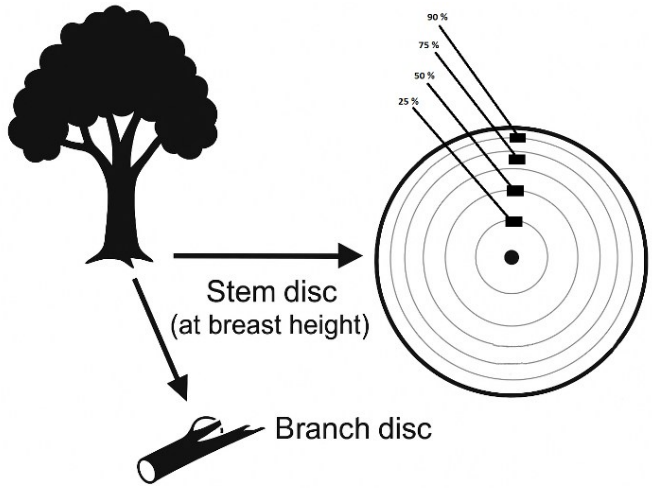

Fig. 1. The location of fiber sampling

Biometrics Measurements

The following fiber dimensions were measured: fiber length, fiber diameter, lumen diameter, and cell wall thickness. These values were then used to calculate papermaking indices using Eqs. 1 to 4 as below,

$$\text{Slenderness coefficient} = L/D \quad (1)$$

$$\text{Flexibility ratio} = C/D \quad (2)$$

$$\text{Runkel ratio} = 2V/C \quad (3)$$

$$\text{Rigidity ratio} = V/D \quad (4)$$

where L = fiber length (µm), D = fiber diameter (µm), C = lumen diameter (µm), and V = cell wall thickness (µm).

Methods

The fibers were separated using the Franklin maceration method (Franklin 1954), which involves immersing samples in a 1:1 (v/v) solution of hydrogen peroxide and glacial acetic acid at 62 °C for 48 h. After maceration, thirty intact fibers from each sample were selected for measurement under an optical microscope at 10× and 40× magnifications.

One-way ANOVA was used to evaluate differences among species and radial positions. Duncan's multiple range test ($p < 0.05$) was applied for post-hoc comparisons. The letters (a, b, c, *etc.*) displayed in the figures represent statistical groupings derived from this test; groups that share the same letter are not significantly different.

RESULTS AND DISCUSSION

Fiber Length

As shown in Fig. 2, the maximum average fiber length (1282 µm) was recorded in apricot stem at the 50% radial position, while the minimum (835 µm) occurred in apricot branch at 25%. Overall, fiber length was consistently higher in stems than in branches across all three species ($p < 0.01$). This pattern reflects fundamental differences in wood formation: stem fibers develop under steady axial growth with a greater proportion of mature tissue, whereas branch fibers contain more juvenile zones and are exposed to mechanical disturbances, both of which restrict fiber elongation (Hassan *et al.* 2020; Guo *et al.* 2022; Andze *et al.* (2024).

Longer hardwood fibers generally contribute to stronger and more cohesive paper structures, as they provide greater effective bonding length during sheet formation. The stem fibers of apricot, plum, and cherry therefore offer more favorable geometry for tensile and burst strength development, whereas branch fibers—with their shorter length and higher juvenile characteristics—tend to form weaker networks and may require blending, depending on the target paper grade (Mirshokraei 2003; Mahdavi *et al.* 2010).

The broader length variability observed in apricot suggests stronger anatomical contrast between its stem and branch wood, which may influence optimal mixing ratios when designing pulp blends from orchard residues (Bahmani *et al.* 2021; Hosseini 2000).

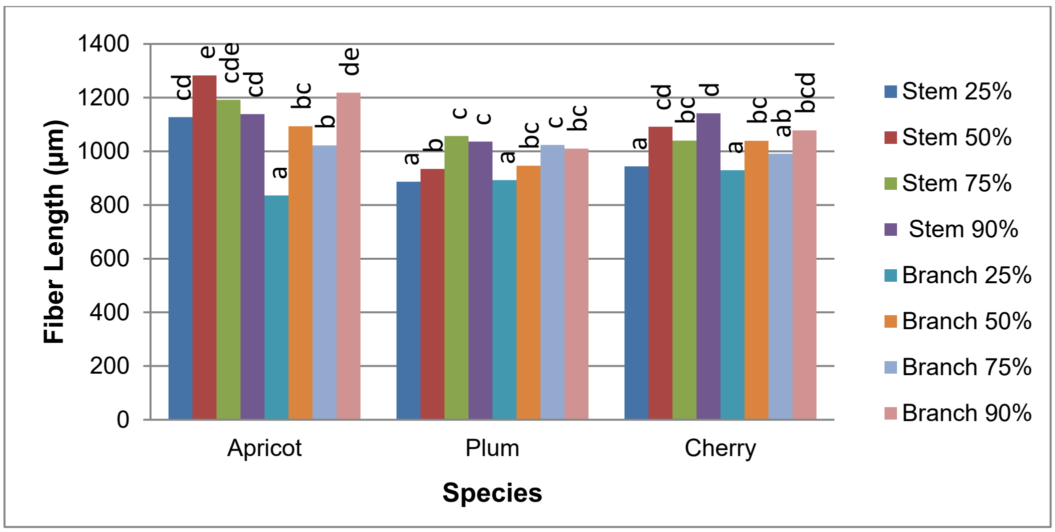

Fig. 2. Average fiber length in stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences ($p < 0.05$).

Fiber Width

According to Fig. 3, the widest fiber (21.9 µm) was measured in cherry branch wood at the 25% radial position, while the narrowest (13.2 µm) was recorded in plum stem at the same position. On average, fiber diameter was significantly greater in branches than in stems for all species ($p < 0.01$), (Hassan *et al.* 2020; Guo *et al*. 2022).

Branch fibers generally exhibited larger diameters due to higher proportions of juvenile tissue and less uniform radial growth, factors that promote greater lateral cell expansion. Increased fiber width can reduce fiber–fiber contact area and, if not accompanied by proportional lumen or wall development, may limit bonding efficiency in hardwood pulps (Andze *et al.* 2024; Bahmani *et al.* 2021).

Cherry displayed the widest fibers in both organs, which is consistent with its coarser anatomical pattern, while plum showed the narrowest diameters, suggesting tighter fiber packing and the potential for producing denser, smoother sheets. These species-specific differences in fiber width underscore the need for tailored pulping and blending strategies to achieve desired paper properties (Zobel and Buijtenen 1989).

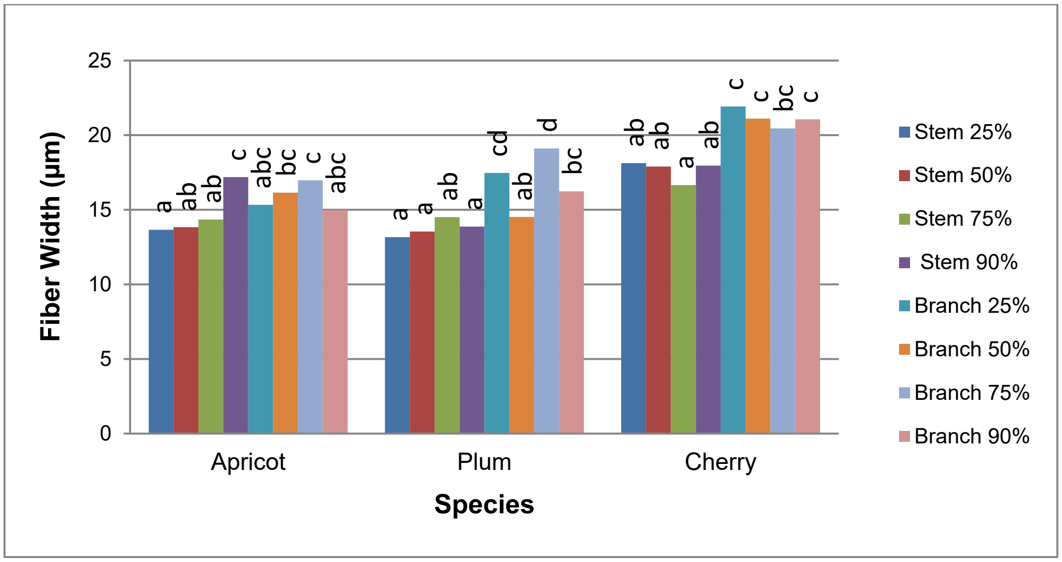

Fig. 3. Average fiber diameter tree stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences ($p < 0.05$).

Lumen Diameter

As shown in Fig. 4, the largest average lumen diameter (10.91 µm) was found in cherry branches at 90%, while the smallest (4.99 µm) was in plum stem wood.

A clear increasing trend from pith to bark was observed in cherry and apricot species. The outward increase in lumen diameter from pith to bark reflects typical maturation patterns in hardwoods, where later-formed fibers develop larger conducting spaces due to improved physiological efficiency rather than purely cambial age. Larger lumens can enhance fiber collapsibility during refining, enabling better surface contact and improving inter-fiber bonding and sheet consolidation (Hassan *et al.* 2020; Guo *et al.* 2022).

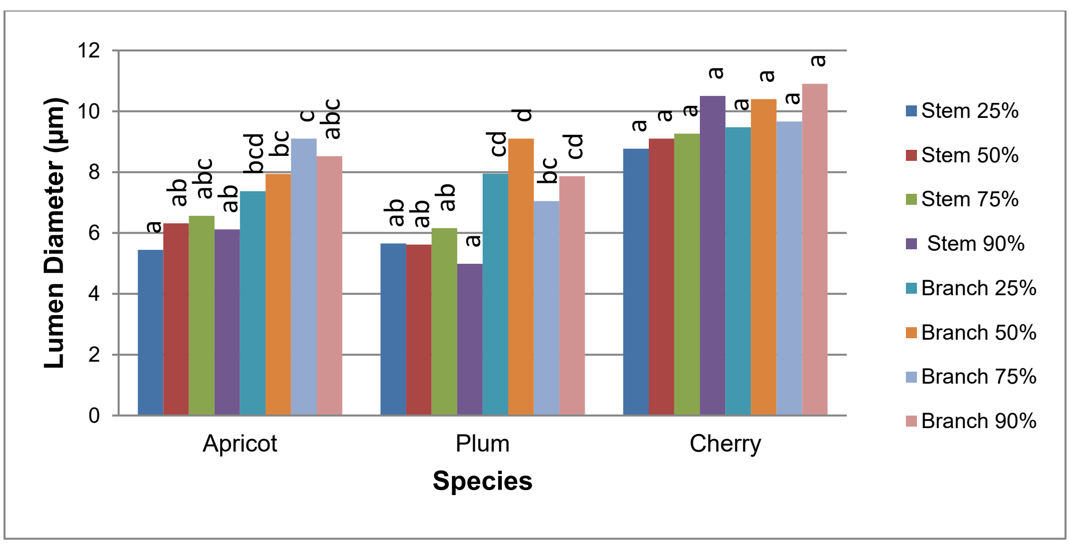

Fig. 4. Average lumen diameter of wood fiber stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences ($p < 0.05$).

Plum exhibited the smallest lumens across both organs, indicating stiffer and less collapsible fibers that may produce denser but potentially less conformable pulps. In contrast, cherry—with markedly larger lumens, especially in branch wood—tends to yield fibers that collapse more readily, provided that wall thickness remains moderate. This combination generally supports better bonding potential and more uniform network formation in papermaking (Andze *et al.* 2024; Bahmani *et al.* 2021).

Cell Wall Thickness

Figure 5 shows that the maximum wall thickness (6.22 µm) occurred in cherry branches at the 25% radial position, while the minimum (2.71 µm) was observed in plum stems at 50%. Wall thickness increased outward in all species, reflecting the formation of structurally reinforced latewood fibers. Thicker walls reduce fiber collapsibility and flexibility, which can limit bonding efficiency, whereas thinner walls generally promote better sheet consolidation in hardwood pulps (Hassan *et al.* 2020; Bahmani *et al.* 2021).

Cherry exhibited the greatest wall thickness in branch wood, likely due to higher mechanical loading in fruit-bearing limbs. These stiff, less collapsible fibers can increase bulk but lower bonding potential. In contrast, the thinner-walled fibers of apricot and plum allow greater flexibility and collapse during papermaking (Andze *et al.* 2024).

Overall, the combined effects of wall thickness, lumen size, and fiber length indicate that stem wood—particularly in apricot and cherry—offers a more balanced anatomical profile for strength-oriented hardwood pulps, whereas branch wood shows greater variability and may require selective blending (Rasooly *et al.* 2007).

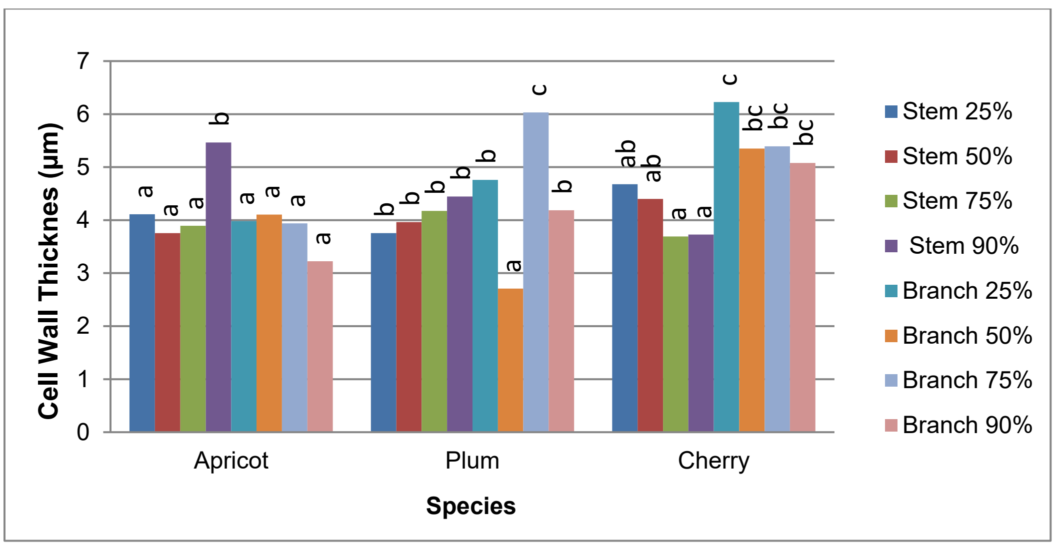

Fig. 5. Average cell wall thickness wood fiber stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences ($p < 0.05$).

Paper Making Ratio

Slenderness coefficient

As shown in Fig. 6, the slenderness coefficient generally increased from pith to bark in both stem and branch wood, reflecting the concurrent rise in fiber length relative to diameter. Stem wood consistently exhibited higher values than branch wood, in line with its longer and more mature fibers (Hassan *et al.* 2020; Guo *et al.* 2022; Tırak Hızal and Birtürk 2024).

Higher slenderness ratios indicate more favorable fiber geometry for papermaking, as elongated fibers with lower relative diameter improve network interlocking and contribute to stronger and more coherent sheets. Accordingly, the higher values observed in stem wood suggest better reinforcement potential compared with branch fibers (Andze *et al.* 2024).

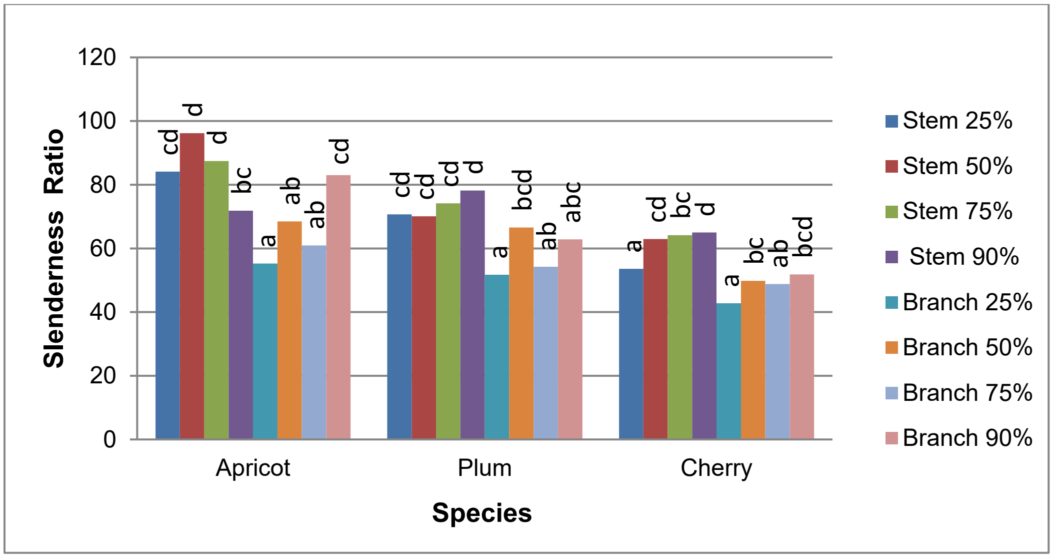

Fig. 6. Average Slenderness coefficient wood fiber stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences (p < 0.05).

Flexibility and Rigidity

As shown in Figures 7 and 8, the flexibility and rigidity ratios increased from pith to bark in all species, reflecting changes in fiber wall structure with maturation. The increases were statistically significant in apricot and plum ($p < 0.01$) and moderate in cherry ($p < 0.05$), (Andze *et al.* 2024).

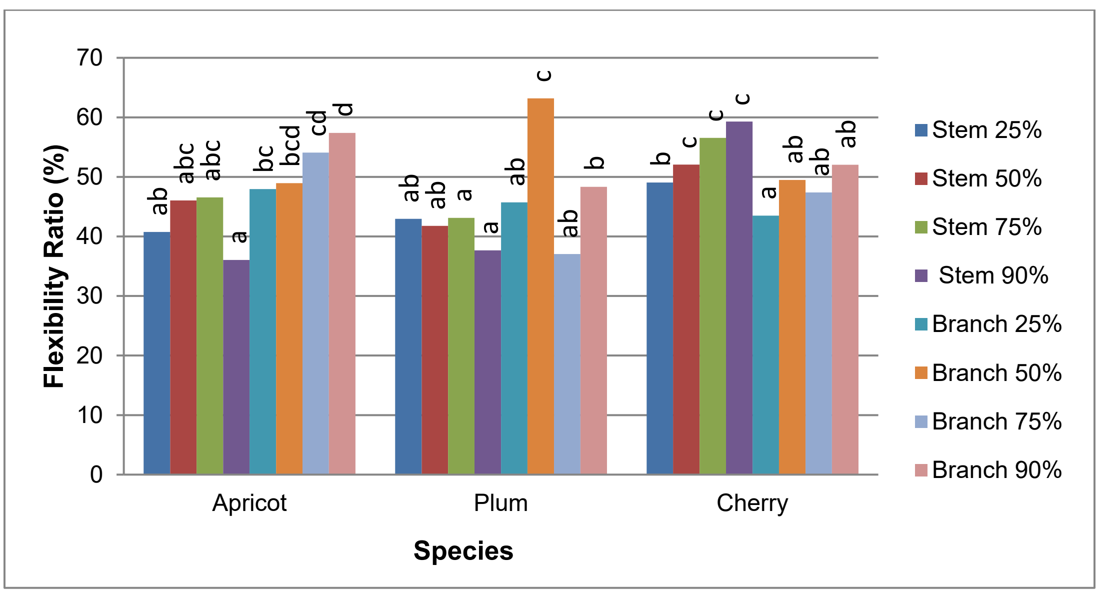

Fig. 7. Flexibility ratio average of wood fiber stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences (p < 0.05).

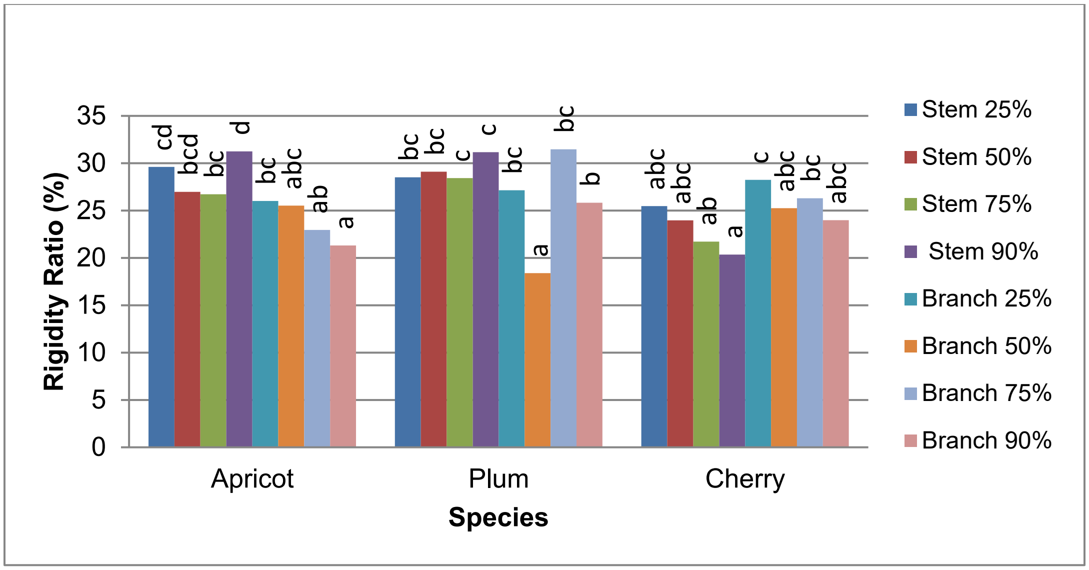

Fig. 8. Rigidity ratio average wood fiber stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences ($p < 0.05$).

Apricot and plum showed higher flexibility ratios in branches, whereas cherry displayed higher values in stem wood. Greater flexibility indicates fibers that collapse more readily during refining, improving surface contact, bonding potential, and sheet consolidation. In contrast, higher rigidity ratios—characteristic of thicker-walled or less collapsible fibers—tend to reduce conformability and may contribute to bulkier but less dense sheets (Rasooly *et al.* 2007; Hassan *et al.* 2020; Guo *et al.* 2022).

Runkel Ratio

As shown in Fig. 9, the Runkel ratio decreased from pith to bark in all three species, reflecting reduced relative wall thickness as fibers matured.

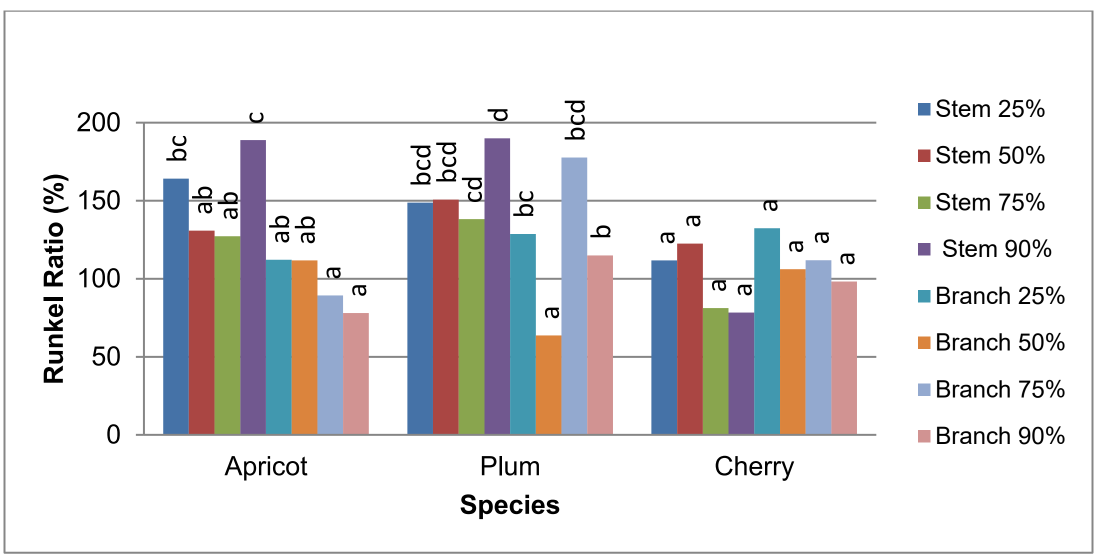

Fig. 9. The average Runkel wood fiber stem and branches of apricot, plum and cherry; different letters indicate statistically significant differences ($p < 0.05$).

The decline was most pronounced in apricot and plum ($p < 0.01$), while cherry showed a more moderate trend. Apricot and plum exhibited higher Runkel values in branches, whereas cherry showed higher values in stem wood (Andze *et al.* 2024).

Lower Runkel ratios indicate thinner walls relative to lumen size, resulting in fibers that collapse more readily and form stronger, more uniform sheets. Ratios below 100% are generally considered favorable for hardwood pulping. Higher values—associated with stiffer, less collapsible fibers—tend to reduce bonding efficiency and may lead to bulkier but mechanically weaker networks (Hassan *et al.* 2020; Guo *et al.* 2022; Bahmani *et al.* 2021).

Based on these results, the stem wood of apricot and plum shows more desirable Runkel characteristics for papermaking, while branch wood, with its higher ratios, may require controlled blending or specific process adjustments depending on the target product (Rasooly *et al.* 2007).

Overall, the combined anatomical and papermaking indices observed in this study indicate that the stem wood of apricot, plum, and cherry provides a favorable balance of fiber length, wall thickness, lumen size, and collapsibility. These characteristics are comparable to those of many commonly used hardwood pulps and suggest that fruit tree stem wood can supply technically acceptable fibers for pulp and paper manufacturing. Considering the large annual volume of orchard pruning and tree replacement in countries with limited forest resources, these species represent a practical and renewable lignocellulosic source (Guo *et al*. 2022; Bahmani *et al.* 2021; Tırak Hızal and Birtürk 2024).

It is also important to note that the availability of stem and branch wood differs in practical harvesting systems. Branch wood is generated annually through routine pruning and therefore represents a continuously renewable but lower-volume resource. In contrast, stem wood becomes available mainly when fruit trees reach the end of their productive lifespan and are replaced, yielding larger volumes of higher-quality wood at longer intervals. This difference in supply cycles helps explain the distinct roles each organ can play in fiber sourcing for pulp and paper production (Andze *et al.* 2024).

CONCLUSIONS

1. The results of this study highlight the significant differences in fiber biometry between stems and branches of wood from apricot, plum, and cherry trees, all of which have potential as alternative raw materials for papermaking. Across all species, stem fibers exhibited greater length, lower lumen diameter, and higher slenderness and rigidity ratios compared to branch fibers. These characteristics make stem wood more suitable for producing stronger, higher-quality paper.
2. Branch wood typically had wider fibers and larger lumen diameters, which contribute to higher flexibility ratios, it also showed higher Runkel ratios—an indicator that may negatively affect paper opacity. Nevertheless, with proper processing, branch wood could still be partially incorporated into pulp blends (up to 40%, as noted by Zeinaly *et al*. (2011), offering a cost-effective and accessible fiber source.
3. Overall, fiber dimensions such as length, width, lumen diameter, and wall thickness—along with calculated biometric indices—play crucial roles in determining fiber

suitability for papermaking. The consistent increase in favorable properties from the pith to the bark also emphasizes the importance of radial position in fiber selection.

4. These findings support the use of fruit tree wood—particularly stem sections—as a sustainable and technically viable raw material for pulp and paper production. The favorable fiber dimensions and papermaking indices observed in this study, together with the abundant availability of orchard residues in regions with limited forest resources, highlight the potential of these species as alternative lignocellulosic sources.

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Article submitted: April 26, 2025; Peer review completed: May 29, 2025; Revised version received: January 5, 2026; Accepted: January 31, 2026; Published: February 16, 2026.
DOI: 10.15376/biores.21.2.3158-3168