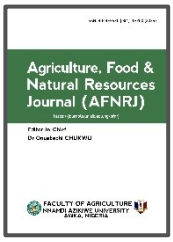
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Review Article

Appraisal of the impact of knotty tissues on the wood properties utilization: A Systematic review

OPEN ACCESS

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ABSTRACT

This study comprehensively reviews the influence of knots on the physical, mechanical, and chemical properties of wood, with particular emphasis on their implications for material performance utilization. Knots are anatomically distinct from surrounding wood tissue, being denser, harder, more resinous, and exhibiting different shrinkage behavior. Several experimental results indicate that wood density increases with increasing knot area in the cross section, while volumetric shrinkage decreases. In contrast, mechanical properties such as bending strength, modulus of elasticity (MOE), and impact bending strength show a pronounced reduction as knot area increases. Specimens containing a high proportion of knots also exhibit lower compression strength parallel to the grain compared with clear wood. Hardness values are significantly higher within knotted regions, whereas adjacent knot-free areas display reduced hardness. Beyond mechanical performance, knots adversely affect appearance quality, machining behavior, adhesive performance, and chemical uniformity, thereby reducing the overall use value and economic value of wood products. Although the higher density of knots has limited influence on the bulk density of wood, suggesting that knotty clear wood may be treated similarly in density-based applications, the presence of knots significantly alters other critical properties that govern structural performance and processing efficiency. These findings provide a systematic understanding of the role of knots in wood quality and serve as a baseline for material selection, grading, and utilization strategies in wood-based industries.

KEYWORDS: *Knot, Machining performance, Mechanical properties, Physical properties, Wood quality*

INRODUCTION

Wood is a renewable natural resource, which has several advantages such as, easy processing, good stability, and a large strength-to-weight ratio. In addition, wood also has unique material properties excellent environmental characteristics (Bruno, *et al.,* 2023; Han, *et al.*, 2023). Trees spontaneously produce some natural defects during growth; knots are one of the most common defects (Zhang, *et al.,* 2024; Karaszewski, *et al*., 2013). However, there are many defects in wood due to physiology, pathology, human reasons common out of these wood defects include knots (Han *et al.*, 2023; Rocha *et al.*, 2018). Wood defects can be categorized as either natural (growth defects) or defects created during wood processing. The former defects are visible, but internal defects (mostly knot) are invisible (Jan Oscarrsson, *et al.,* 2023: Hossein, *et al.*, 2011).

A knot is a particular type of imperfection in a piece of wood which affects the physical mechanical properties of wood, making it unsuitable for some applications rendering it undesirable even if no defect is apparent from the outside view (Hossein *et al.*, 2011). Knots decrease the strength of wood mainly because of interrupting direction of grain, localized

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steep slope of grain concentrates around knots (Bruno, *et al.,* 2023; Kaiser Kaiser, 2019). Knots are well known to contribute to the increases in compression strength, hardness, shear characteristics of the wood decrease the tensile bending strength (Kaiser Kaiser, 2019). It causes uneven wear on the surfaces, give trouble because of the checking with moisture changes, make difficulty in painting increase for cutting forces (As N*, et al.,* 2008). The occurrences of knots in the wood are anatomical defects that damage or render wood useless for certain applications (Rocha *et al.*, 2018). Knots also cause deviations in the fiber direction affecting the anatomical structure of the wood (Bruno, *et al.,* 2023; Rocha *et al.*, 2018).

The regions around the knots present inclined fibers or some type of deviation have lower stiffness strength against force applied in the direction parallel to the length than in comparison with areas of straight oriented fibers (Košíková, 2009). The ability of wood to resist loads is greatly affected by the presence of knots (Jan Oscarrsson, *et al.,* 2023; As N, *et al*., 2008). Knots show different characteristics from stem roots, the form, size, the numbers of knots in the tree depend on tree species, age of tree, site conditions, site composition, etc. Depending on the location in wood, type, size, position, number, knots diminish strength properties of wood (As N, *et al*., 2008). Besides mechanical properties, knots affect sawing, planning, gluing, finishing, drying, shrinkage of wood. Knots do not lower the stiffness of a timber appreciably, but they reduce its tensile strength (As N, *et al*., 2008). Hence, they are of greater significance in joists, beams similar timbers, than they are in columns. In beams, the weakening influence of knots is greatest when they occur in the vicinity of the maximum bending stress on the bottom of the beam (tension zone); they are of less importance when they occur near the top of the beam (compression zone) (As N, *et al.,*2008). Reductions in strength properties, resulting from knots, increases at a faster rate than the proportional increase in area of the knot (Zhang, *et al.,* 2024; Dinwoodie, 2001; Desch, 1973).

Knots are usually considered one of the most common wood defects are specific imperfections in the wood that reduce its quality value (Jan Oscarrsson, *et al.,* 2023; Quin *et al.*, 2019). It is the most common defect in timber, lumber, any other wood-based products, are denser, harder and contains more resin reaction wood than that of the surrounding wood tissue (Maria Ferna, V.R, 2018; As N, *et al.,*2008). Knots can be divided into live, dead knots, crack, edge, inter grown sound knots (Quin *et al.*, 2019; Lowell *et al*., 2014). Therefore, this review article is specifically meant to raise awareness of the problem associated with wood knots its effects on wood properties as to develop a strategy for effective utilization, these findings can be used as a baseline for understanding the impact of knots on wood quality to end-users' forestry researchers (Guillerno, 2008).

The method of information gathering data collection used during the conduct of this review process for the study was based on Scott's (1990) principle called Document Analysis. This document analysis was reported to be based on three pivots. They are;

Originality- It was ensured that all the literature materials consulted were original articles.

Authenticity- The source of all the articles used in the preparation of the review paper is authenticated.

Credibility-The credibility of all articles used in this review paper are credible authors known scientist.

Meanwhile, the entire document materials used for writing this review article the cited references throughout the article is a tangible proof as regards this topic.

WOOD KNOTS

Description of Wood Knots

Knots are portions of branches that become included into the tree trunk during growth influence the strength properties of a piece wood (Bruno, *et al.,* 2023; Kaiser Kaiser, 2019). Knots are the embedded basal portion of a branch in the trunk that cause deviations in the woody tissue, as well as difficulty during processing, loss of mechanical strength in the work piece reduced wood quality (Krutul *et al*., 2013; Vek *et al.*, 2014).

Types of Observed Wood Knots

Li J (2010) research reported that knots are darker in color than regular wood. Due to the dead knot's separation from the surrounding tissue, the edge's color significantly changes, resulting in a hard black scar. The color of the live knot progressively deepens and changes, and there is a distinct border between it and the surroundings. Below are the known types of knots;

Live Knots**:** Live knots are formed from the living part of a branch; they are inter-grown with the wood (Bruno, *et al.,* 202; Lowell *et al*., 2014).

Dead Knots**:** A fully dark knot is called Dead knot are formed from the dead part of a branch, (Zhang, *et al.,* 2024; Lowell *et al*., 2014). Dead knot has slightly darker area sometimes have similar features as live knot (Quin *et al.*, 2019; Mohan Venkatachalapathy, 2012).

Crack Knot**:** A crack knot is a crack structure inside the wood portion that affects the wood strength its appearance (Mohan Venkatachalapathy 2012; Zhou, *et al.,* 2021).

Edge Knot**:** These kinds of knot are formed on the edge of the timber (Zhang, *et al.,* 2024).

Inter-Grown Knot**:** A knot that is enclosed with strong bark areas is called Inter grown knot. There is a thin ring in these knots with big bark pockets formed in the knots (Zhou, *et al.,* 2021; Zhou, *et al.,* 2016; Mohan Venkatachalapathy 2012).

Sound Knot**:** A sound knot is also known as clear knot; it is a kind of knot that is very common but with no defects not harmful (Zhou, *et al.,* 2021). There are few circular shaped curves that reflect the age of the branches that is observed in the

images of typical sound knots. When compared to the background wood, sound knots have slightly dark colors various textures but it is much brighter than dead knot (Zhou, *et al.,* 2016; Mohan Venkatachalapathy, 2012).

EFFECTS OF KNOT ON WOOD PROPERTIES UTILIZATION

Knot has effect on different wood properties such as appearance of wood, mechanical physical properties of wood, wood machining performance, chemical composition of wood, as well as glue performance of wood (Zhang, *et al.,* 2024; Jan Oscarrsson, *et al.,* 2023)

Effect of Knot on the Physical Properties of Wood

The wood color of the knot is deeper than the normal material nearby (Jan Oscarrsson, *et al.,* 2023; Zhou, *et al.,* 2021; Li, 2010 & Nusret, *et al.,* 2006).). The unique pattern deep color give people a beautiful stimulation, a dynamic floating feeling, giving the environment a sense of luxury. However, it has been reported that most of the times the knot destroyed the appearance consistency of the whole piece of wood. According to (Zhang, *et al.,* 2024; Bruno, *et al.,* 2023; Zhao *et al.,* 2016), the texture of the knot is obviously different from the surrounding, it is distorted to varying degrees, showing a unique texture changing physical mechanical properties of wood (Bruno, *et al.,* 2023). Wood color is closely related to the quality assessment of wood products, which is related to the visual aesthetics of wood products their decorative properties, thus affecting their economic, collecting, artistic value (Bruno, *et al.,* 2023; Lyu *et al*., 2023). Wood color is a fundamental property of wood, its chromaticity index is distributed among wood species (Maria Ferna, 2018)

Effect of Knot on the Mechanical Properties of Wood

The mechanical properties of wood are its fitness ability to resist applied or external forces (Zhang, *et al.,* 2024). By external force is meant any force outside of a given piece of material which tends to deform it in any manner (Zhou, *et al.,* 2021; Dinwoodie, 2021; Record, 1914). The effect of knots on mechanical properties of wood can be influenced by factors such as: cross section dimensions occupied by the knot, knot type, distribution location distribution of the stresses presents in the timber (Bruno, *et al.,* 2023; Gupta *et al.,* 2004**;** Nagai *et al.,* 2010**).**

The density water content of the knots is significantly different from the surrounding wood tissue (Jin, 2016). During the drying process, the knots may fall off cause holes. In the mechanical properties test carried out by (Hu *et al.,* 2018) have shows that the knots reduce the tensile compressive strength of the wood, but improve the horizontal compressive strength the shear strength. The knots of larch increased their flexural strength (Zhang, *et al.,* 2024; Zhang *et al.,*2018).

Based on the research report by Ruan *et al*., 2024, Zhang, *et al.,* 2024 reported the variations in physical mechanical properties between clear knotty wood of Chinese fir shows that the knotty wood exhibited significantly lower values in ultimate stress in compression parallel to grain, tensile strength parallel to grain, bending strength, modulus of elasticity in bending, impact bending strength compared to clear wood, indicating a notable disadvantage in mechanical properties of the knotty specimens (Zhang, *et al.,* 2024; Jan Oscarrsson, *et al.,* 2023). This discrepancy can be attributed to the more disordered fiber structure in knotty wood, weaker fiber connections, the stress concentration induced by knots, all contributing to the deterioration of wood mechanical properties (Ruan *et al*., 2024). Moreover, the presence of natural defects cracks in knotty wood might diminish its load-bearing capacity, making it more prone to damage from external forces.

The surrounding complex growth environment of knots could have also led to inferior inherent wood quality (Ruan *et al*. 2024; Jan Oscarrsson *et al.,* 2023).

Effect of Knot on the Wood Machining Performance

The hardness of knots is greater than the hardness of wood itself, the knots may be carbonized due to high temperature during sawing (Jan Oscarrsson, *et al.,* 2023; Hu, *et al.,* 2018). At the same time, the angle of the knot is large, which greatly shortens the service life of the wood tools when processing wood. In the processing of veneers, the boiling softening of the knots before the wood is made is particularly important (Ruan *et al*., 2024**;** Hu, *et al.,* 2018).

Effect of Knot on the Chemical Composition of Wood

Microscopically, it was reported that the internal fibers of the wood deviate from the knot, resulting in imperfections in the fibers inside the wood (Maria Ferna, 2018; Lukacevic Kler 2019). Studies by have shown that extracts from the knot are more abundant than other parts, the essential oil content is significantly higher than other parts (Jan Oscarrsson, *et al.,* 2023; Vek *et al.,*2014). Likewise, knot depicts common knot kinds and characteristics. According to Trincado G's knot prediction model the majority of knots are conical, with only a small percentage seeming cylindrical. Huang *et al.,* (2011) and others discovered that knot formation and distribution are influenced by genes in addition to site circumstances and environmental factors. For instance, the number of knots in various tree species varies greatly. Poplar, eucalyptus, and other knots have less knots than larch, camphor pine, and other knots.

Effect of Knot on the Wood Glue Performance

Huang *et al.,* (2011) reported Knot will reduce the gluing properties of the wood (Lin *et al.,* 2012); the size of the knot type will have significant impact on the gluing properties of wood (Vek *et al.,* 2014; Xu P. 2002). Generally, dead knot has a greater effect on wood quality than live knot. However, it was found by (Zhang, *et al.,* 2024; Zhou, *et al.,* 2016) that the effect

of the dead knot on the bending strength of the live knot is small it was explained in two ways:

i. The texture slope of living knot is greater than that of dead knot.

ii. Cracking due to drying of the living knot surrounding wood. Considering again that the live knot can resist several kinds of stress, while the dead knot cannot, it can be concluded that the influence of the dead knot the live knot on the stress is basically equal.

Effect of Knot on Wood Swelling Shrinkage

Dead knots contain more extracts, the chemical composition of the extracts has a greater influence on water absorption loss, similar to other observations studies carried out by Ruan *et al*., 2024; Zhou *et al.,* 2021.

CONCLUSION AND RECOMMENDATIONS

Knots remain one of the most influential natural defects affecting wood quality and utilization. Their presence alters grain orientation, density distribution, and structural continuity, thereby affecting the physical, mechanical, chemical, and bonding properties of wood. Beyond reducing strength performance in several loading conditions, knots also contribute to machining difficulties, reduced tool efficiency, dimensional instability, and poorer gluing performance. The study therefore establishes that proper understanding of knot characteristics is essential for accurate wood grading, efficient processing, improved product performance, and sustainable utilization of timber resources. The findings further provide useful guidance for forestry professionals, wood processors, and tree breeders in enhancing wood quality assessment and utilization strategies.

The study recommended that advanced wood grading and processing techniques should be adopted to properly identify and classify knot characteristics before utilization in structural and industrial applications. Furthermore, tree improvement and silvicultural practices aimed at reducing knot formation should be encouraged to enhance timber quality and improve the performance of wood products.

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Ethical Statement

Not applicable.

REFERENCES

As, N, Dundar T. & Umit, B. (2008). Effect of Knots on the physical mechanical properties of Wood. *Forestist,* 58 (4): 1-13. https://doi.org/10.17099/jffiu.76055

Bruno, M. B., C. Br W., Marcelo, L. R., Alessra, S. B., & José Nivaldo Garcia, 2023. Influence of knots on the adhesion of wood from young *Eucalyptus gris* plantations**.** *European Journal of Wood and Wood Products, 83*:3. https://doi.org/10.1080/17480272.2023.2208094

Desch, H.E., (1973): Timber. Its structure properties. Fifth Edition, Macmillan.

Dinwoodie, J.M., (2001). *Timber: Its Nature Behaviour*; *Taylor and Francis:* Abingdon, UK,

Gupta, R., Basta. C. & Kent, M. S., (2004). Effect of knots on longitudinal shear strength of Douglas-fir using shear blocks. *Forest Products Journal,* 54 (11): 77-83.

Guillermo Trincado, (2008). A model of Knot shape volume in Loblolly pine trees. *Wood Fiber Science,* 40(4), 634 – 646.

Han, S., Jiang, X., and Wu, Z., (2023). An improved YOLOv5 algorithm for wood defect detection based on attention. *IEEE Access*.71 – 800. https://ieeexplore.ieee.org/iel7/6287639/10005208/10177807.pdf

Huang, S. Y., Wang, J. H., Lyu, J. .X & Lei, Y. C. (2011). Progress in World knot Research *China Forest Products Industry*. 38 3-7

Hu, M., Briggert, A., Olsson, A., Johansson, M., Oscarsson, J. & Säll, H. **(**2018). Growth Layer Fibre Orientation around Knots in Norway Spruce: A Laboratory Investigation. *Wood Science and Technology. 52*, 7–27. https://doi.org/10.1007/s00226-017-0952-3

Hossein, M.A., Shahverdi, M. & Roohnia, M., (2011). The effect of wood knot as a defect on modulus of elasticity (MOE) damping correlation. *Notulae Scientia Biologicae*, *3*(3), 145-149. https://www.notulaebiologicae.ro/index.php/nsb/article/download/6119/8358/37220

Jan Oscarsson, ers Olsson, and Bertil Enquist (2011). Strain fields around knots in Norway spruce specimens exposed to tensile forces. *Wood Science and Technology*. https://doi.org/10.1007/S00226-011-0429-8

Jin, R. L. (2016). Discussion on the main points of wood defect wood inspection Technology Friends of Farmers' Wealth. 140p.

Kaiser, S. & Kaiser, M.S., (2019). Comparison of wood knot on wear behaviour of Pine Timber. *Res Eng Structure Mat*, 6 (1), 35-44. https://jresm.org/article/resm2019-115ma0207/

Karaszewski, Z., Bembenek, M., Mederski, P.S., Szczepanska-Alvarez, A., Byczkowski, R., Kozlowska, A., Michnowicz, K., Przytula, W. & Giefing, D.F. **(**2013). Identifying beech round wood quality-distribution of beech timber qualities influencing defects. *Drew. Pr. Nauk. Doniesienia Komun.*, *56*, 39–54. https://bibliotekanauki.pl/articles/52715.pdf

Košíková, B. (2009). Morphological chemical characteristics of stem knot poplar wood. *Wood Research*; 54 (3): 117-122. https://www.woodresearch.sk/wr/200903/13.pdf

Krutul, D, Zielenkiewicz, T., Zawadzki, J., Radomski A, Antczak A, and Drożdżek M. (2013). Influence of knots on the content of chemical substances in knot adjacent oak wood (*Quercus petraea* Liebl.) *Ann. WULS – SGGW Forestry Wood Technology*. 83(1): 112-123. https:doi. https://doi.org/10.1186/s13595-024-01223-0

Li, J., (2010). Ecological properties of wood-wood is a contributor to human health in green environment. *Journal of Northeast Forestry University*. 38 (05) 1-8. https://biobus.swst.org/bpbj/index.php/bpbj/article/download/52/93/0.

Lin, L. Y., He, S. & Fu, F., (2012). Effects of knot on wood Gluing properties. *China Forest Products Industry*. 26 (04) 12-15.

Lukacevic, M., Kler, G., Hu, M., Olsson, A., & Füssl, J. (2019). A 3D Model for Knots Related Fiber Deviations in Sawn Timber for Prediction of Mechanical Properties of Boards. *Materials Design*, *166,* 107617. https://doi.org/10.1016/j.matdes.2019.107617

Lowell, E.C., Maguire, D.A., Briggs, D.G., Turnblom, E.C., Jayawickrama, K.J.S. & Bryce, J. (2014). Effects of Silviculture Genetics on Branch/Knot Attributes of Coastal Pacific Northwest Douglas-Fir Implications for Wood Quality-A Synthesis. *Forests*, *5*, 1717–1736. https://www.fs.usda.gov/pnw/pubs/journals/pnw_2014_lowell001.pdf

Lyu, J.; Qu, H. & Chen, M., (2023). Influence of Wood Knots of Chinese Weeping Cypress on Selected Physical Properties. *Forests*, *14*, 1148. https://doi.org/10.3390/f14061148.

Rocha, M. F. V. (2018). Wood Knots Influence the Modulus of Elasticity Resistance to Compression. FapUNIFESP (SciELO). Floresta eAmbiente. https://doi.org/10.1590/2179-8087.090617

Mohan, S. & Venkatachalapathy, K. (2012). Wood knot classification using bagging. *International Journal of Computer Applications*, 51. 50-53 https://doi.org/10.5120/8146-1937

Nagai H, Murata K, & Nakano T. (2010). Strain analysis of lumber containing a knot during tensile failure. *Journal of Wood Science,* 57(1): 114-118.

Nusret, A.S. Göker, Y. & Dündar, T., (2006). Effect of knots on the physical mechanical properties of Scots pine (*Pinus sylvestris* L.). *Wood Research,* 51(3). 51-58.

Qin, G.; Hao, J.; Yang, J.; Li, R.; and Yin, G., (2019). Branch occlusion discoloration under the natural pruning of *Mytilaria laosensis*. *Forests 10*, 892.

Record, S.J., (1914). *The mechanical properties of wood.* 165. New York: Wiley.

Rocha, M.F.V., Costa, L.R., Costa, L.J., Araújo, A.C.C.D., Soares, B.C.D. and Hein, P.R.G., (2018). Wood knots influence the modulus of elasticity resistance to compression. *Floresta e Ambiente*, *25*, e20170906.

Ruan, Y., He, Z., Fan, S., Chen, Z., Li, M., Ma, X. and Sun, S., (2024). Variations in Physical Mechanical Properties between Clear Knotty Woods of Chinese Fir. *Forests*, *15* (11): 2007

Scott's (1990). A Matter of Record, Documentary Sources in Social Research. Cambridge: Polity Press

Trincado, G. & Burkhart, H. E. (2008). A model of knot shape and volume in Loblolly pine trees *Wood Science and Technology*.40 (4) 634-646.

Vek, V., Oven, P., Ters, T., Poljanšek, I, & Hinterstoisser, B. (2014). Extractives of mechanically wounded wood knots in beech. *Holzforschung* 68 (5): 529-539. http://dx.doi.org/10.1515/hf-2013-0003.

Xu, P. (2002). Estimating the influence of knots on the local longitudinal stiffness in radiata pine structural timber. *Wood Science Technology Journal* 36(6): 501-509. http://dx.doi.org/10.1007/s00226-002-0156-2.

Zhang, X., Sun, H., Xu, G., Duan, Y., Van den Bulcke, J., Van, Acker, J. & Shi, J. (2024). Understanding the effect of knots on mechanical properties of Chinese Fir under bending test by using X-ray computed tomography digital image correlation. *Forests*, *15*, 174. https://doi.org/10.3390/f15010174

Zhang X Y, Jiang X M and Yin, Y. F., (2018). Effect of node on Acoustic ultrasonic parameters bending resistance of larch wood. *Wood Processing Machinery*. 29(01) 13-33. https://iopscience.iop.org/article/10.1088/1757-899X/738/1/012027

Zhao, P J, Zhou S. R., and Ye, L. X., (2016). Discussion on the influence of knot on material quality in wood inspection. *Friends of Farmers' Wealth*. 04: 102.

Zhou, F.; Fu, Z.; Gao, X.; Zhou, Y.; and Jiang, J. (2021). Within-tree variation of physical properties of *Acacia melanoxylon* wood. *Chin. J. Wood Sci. Technol.,* 35, 30–36. https://doi.org/10.1016/j.matdes.2013.12.016

Zhou Z, Yin J, Zhou S, Zhou H, and Zhang Y. (2016). Detection of knot defects on coniferous wood surface using near infrared spectroscopy chemometrics. *BioResources* 11(4): 9533-9546, http://dx.doi.org/10.15376/biores.11.4.9533-9546