Journal of Forestry
https://doi.org/10.1007/s44392-025-00050-z

ORIGINAL PAPER

Stakeholders' Attitudes and Perceptions Regarding the Viability of Hardwood Cross Laminated Timber (CLT)

Alexander Bremner[1] · Neelam Chandra Poudyal[1] · Prakash Nepal[2] · Consuelo Brandeis[3] · Adam Taylor[1]

Received: 15 November 2024 / Accepted: 1 July 2025

Abstract

At present, cross-laminated timber (CLT) used in the United States is made with softwood species. With the expanding market for mass timber products, there is growing interest in understanding the technological, economic, social and environmental viability of CLT manufactured from hardwood lumber. Many states across the Southeastern United States produce hardwood lumber but demand for hardwood items has decreased, leading to hardwood production which is now near to record-low levels. Lower hardwood production impacts forest management and rural communities, thereby creating a need for new opportunities for the use of hardwood resources. As little is known about the industry's perception of viability of hardwood CLT, this study used key informant interviews of 20 wood industry professionals, as well as related studies and scientific literature, to shed light on opportunities and barriers related to the viability of hardwood in CLT. The findings show promise for hardwood CLT in terms of mechanical effectiveness, lumber supply, and aesthetic appeal. Potential barriers include higher raw material cost, limited awareness, liability, decay, longevity and a lack of established lumber grading, technical skills, and supporting infrastructure for this use of hardwood lumber. These barriers will need to be overcome if the inclusion of hardwood in CLT is to occur.

Keywords Mass timber · Cross-laminated timber · Hardwood · Key informant interviews

Management and Policy Implications Key aspects surrounding the viability of hardwood CLT include supply and demand, production and manufacturing, construction use and codes, societal perception and acceptance, as well as environmental and sustainability benefits. By interviewing 20 key informants from the wood industry professionals, this study sheds new light on industry perception of the viability of hardwood CLT and synthesizes a list of potential opportunities and barriers for hardwood CLT promotion in the US. Identified key opportunities include mechanical effectiveness, lumber supply, and aesthetic appeal. Barriers include limited awareness, higher cost, liability, decay, and longevity, as well as the lack of established lumber grading, technical skills, and supporting infrastructure. Knowing such opportunities and barriers will be a vital first step toward the success of the hardwood CLT industry in the United States.

Extended author information available on the last page of the article

Published online: 05 August 2025

Introduction

Mass timber products are being considered as a potential building material in high-rise construction. The most commonly-used structural materials for five and higher-story buildings are steel and concrete, both of which involve extensive amounts of greenhouse gas (GHG) emissions in the production process (Junnila & Horvath 2003; Brashaw & Bergman 2021; Abed et al. 2022; Kumar et al. 2024). Wood is a potentially sustainable material that, when produced and used in environmentally conscious ways, shows potential to mitigate GHG emissions in construction (Brashaw & Bergman 2021; Yadav & Kumar 2021; Abed et al. 2022; Kumar et al. 2024; Nepal et al. 2024). Currently, the number of mass timber projects in the US is small compared to traditional construction, but is growing. WoodWorks, a leading non-profit in the wood product sector, reported that 2,205 mass timber projects have been completed as of June 2024 (WoodWorks 2024a, b), which represents almost a 100% increase compared to the 1,114 mass timber projects reported in March 2021 (SkyCiv Industry 2021).

Mass timber encompasses many products and is defined as composites of smaller wood elements to form a larger structural component (Cai et al. 2021; Comnick et al. 2021; Anderson et al. 2024). Cross-laminated timber (CLT) is now approved for use in tall buildings (Walch et al. 1923, Harpole et al. 1979; Bergman et al. 2010; Parajuli & Laleicke 2018), and therefore is the focus of this study. CLT consists of three or more layers of sawn lumber that are placed with wood grains perpendicular to the adjacent layers and secured with adhesive. These panels can be used for floors, walls, or ceilings in mid-to-rise building construction (Abdoli et al. 2022).

Softwood lumber is used in CLT manufacturing because its properties are appropriate for construction purposes, and only softwoods have been available in large, uniform quantities at affordable prices (Adhikari et al. 2020). Consideration of incorporating hardwood lumber in CLT panel construction has arisen in wood products research. There is an abundance of hardwood lumber in many regions of the Eastern US, and its utilization in CLT manufacturing may assist struggling hardwood markets (Brandeis et al. 2021). Research into the mechanical effectiveness of hardwood CLT has shown promise (Aicher et al. 2016; Espinoza & Buehlmann 2018; Adhikari et al. 2020; Palacio-Betancur et al. 2023), but these studies are generally limited in terms of species considered, region of study, and small scale of testing, leading to a need for more research and testing. The US standard for performance for mass timber, including CLT, is the ANSI/APA PRG 320 (which stands for American National Standards Institute/The Engineered Wood Association Performance-Rated 320). The PRG 320 specifies the tests a CLT component must pass to be used in building construction (APA 2020). It is under the PRG 320 that current softwood species such as pine (*Pinus spp.*), spruce (*Picea spp.*), and Douglas fir (*Pseudotsuga menziesii*),commonly used in CLT, have been certified. Currently, yellow poplar (*Liriodendron tulipifera*) is the only hardwood species listed as pre-qualified under the PRG 320 guidelines issued in 2025. Potential development of yellow poplar CLT could increase interest in having other hardwood species added to the PRG 320.

Emerging literature in hardwood mass timber indicates some promising signs. Mechanical performance is a major factor when considering the potential to use hardwood lumber in CLT panel construction. Ehrhart and Brandner (2018) made experimental CLT panels with European poplar, birch, beech, and ash that had rolling shear strength test values greater than those of CLT constructed from Norway spruce, while ash and beech showed exceptional shear strength compared to other species. Crovella et al. (2019) found that two hardwood species (i.e., red maple and ash) met the requirements for CLT construction, while Eastern white pine did not. Nail and screw withdrawal performance in a CLT panel constructed of poplar met standard requirements (Abdoli et al. 2022). Other Harwood species such as red maple and sweetgum have been reported to show the most potential for use in CLT, as well as a veneer (surface layer) over a structural softwood core in a hybrid panel construction (Palacio-Betancur et al. 2023). The above-mentioned studies show that certain hardwood species have the potential to meet, and in some cases exceed, the structural design requirements for use in CLT panel construction.

The cost of lumber is a primary consideration in CLT production. Hardwood lumber price is on average two to three times that of comparable softwood lumber (Timber Update 2023). Researchers have attempted to find new ways of lowering the cost (Crovella et al. 2019; Azambuja et al. 2022), but more studies will be needed in the future. Several studies have evaluated low-grade hardwood lumber from species such as poplar, ash, and maple and found that a significant portion of low-grade boards from some species meet the minimum requirements under the PRG 320 (Azambuja et al. 2022) or the PRG 320 standards for stiffness and shear strength (Crovella et al. 2019). Low-value European and Chinese eucalyptus have also been found to meet structural standards for CLT panel construction (Liao et al. 2017; Ettelaei et al. 2022). Accordingly, the use of smaller-diameter lumber or low-grade hardwood lumber can significantly lower the cost of CLT panel manufacturing, lessening potential financial constraints.

Despite the promises of hardwood in CLT manufacturing, the market is yet to develop in the United States. While a few recent studies have assessed the perspectives of CLT manufacturers and other stakeholders (Vlosky et al. 2019a, 2019b, Adhikari, et al. 2020, Schenk et al. 2022), the focus of these studies has been limited to softwood. Of note, Espinoza & Buehlmann (2018) specifically focused on hardwood and drew valuable insights on its feasibility based on a review of literature on the manufacturing and use of CLT. Whether and to what extent the stakeholders in the wood industry themselves perceive the barriers and opportunities, and how the concerns may be alleviated to promote the manufacturing and use of hardwood CLT, remain to be explored. A study on industry perception can complement or validate existing scientific evidence by providing real-world insights into how issues and opportunities are perceived in practice. To address this gap, the objective of this study was to examine stakeholders' attitudes towards the technological, economic, social, and environmental viability of hardwood CLT production and its adoption in construction. This was achieved by adopting a qualitative social science inquiry method involving in-depth interviews of 20 key informants from the wood industry to identify the potential opportunities for, and barriers to, hardwood use for CLT manufacturing in the United States.

Materials and Methods

Key Informants Interviews

A qualitative research method called key informant interview (KII) was adopted to collect data needed in this study. The KII is an in-depth interview methodology that gathers perspectives from highly knowledgeable stakeholders (e.g., industry professionals, researchers, community leaders, or any other person or persons) who have insight into a research topic. This method typically makes use of fewer interview participants when compared to other social science methods (e.g., survey), relying instead on the depth and quality of information provided by the most informed individuals. This method is commonly used in policy analysis or aiding other industry decision-making (Crabtree et al. 1999) and has been used widely to assess perspectives of stakeholders in the forestry sector (Elmendorf & Luloff 2006; Twongyirwe et al. 2018).

The key informants selected for this study were from three groups in the wood industry: sawmill and lumber yard owners, engineers and architects, and wood scientists. Sawmill and lumber yard owners were selected for potential feasibility aspects of production and supply implications. We utilized the member directory of The National Hardwood Lumber Association (NHLA 2023) and consulted with our contacts at the Association to identify and verify sawmill and lumber yards that had been involved in previous wood product research. The NHLA or any member of it did not actively collaborate in the study. Engineers and architects were selected based on previous CLT project experience, or involvement in research around wood utilization in construction. The wood scientists were chosen based on their ongoing or completed research on the novel use of wood products, as indicated by publications, scientific presentations, funded grants, or corporate profiles.

The initial goal of this study was to interview six to eight informants per group. The number of interviews was chosen with the goal of achieving 'information saturation'. Saturation is defined in a qualitative survey methodology as the point at which further interviews do not provide any new information (Saunders et al. 2018). This number can vary depending on the type of study and data being collected; however, it is typically recommended that a total of 15–35 interviews be conducted in a KII (Crabtree et al. 1999). The final number of informants after conducting the interviews was 20, consisting of six sawmill/lumber yard owners, seven engineers and architects, and seven wood scientists. Interviews were conducted between May and August of 2023. Informed consent was secured from participants and interviews were conducted over Zoom or by phone, depending upon the preference of the respondents. The interviews ranged from 45 min to one hour and consisted of 10 questions in the key informant interview checklist (Table 1). Recorded interview audio files were transcribed for coding and analysis.

Sawmill and lumber yard owners were primarily from Tennessee, mainly due to convenience and ease of communicating and interviewing, but one key informant

Table 1 Questionnaire used for conducting key informant interviews

Question #	Key Informant Interview Questionnaire
1	What is your current familiarity with Cross Laminated Timber (CLT)?
2	What are your general thoughts on how CLT may impact the environment, climate, or forests?
3	How would you describe the scope of hardwood CLT production, utilization, or interest currently?
4	How do you think (e.g., aesthetic, structural, adding value) hardwood CLT would compare to softwood CLT?
5	What are ways that consumers may value hardwood CLT (e.g., aesthetic, structural, adding value) compared to softwood CLT?
6	How do you think a hardwood CLT manufacturing facility would impact (e.g., economic, societal, environmental) local and state economies?
7	In what ways could legal and structural constraints (e.g., supply of lumber, code standards) affect the establishment of a CLT mill?
8	In what ways could technical and logistical constraints (e.g., lack of structural grading skills, drying kiln, dimension lumber) affect the establishment of a hardwood CLT mill?
9	(Question a. if participant is positive/question b. If participant is negative) a. What needs to be done (e.g., market assurance, capacity building, subsidy, innovation grant, outreach, and promotion) to make hardwood CLT more successful? b. Why might hardwood CLT not be successful (e.g., lack of market assurance, capacity building, subsidy, innovation grant, outreach, and promotion)?
10	Are there any other comments, concerns, or information that you would like to provide that haven't been asked in the previous questions?

was from Pennsylvania. Based on our familiarity of the type of facilities, processing capacity and current conditions of the hardwood mills in the hardwood region of the United States. Nonetheless, caution should be exercised for some potential regional bias induced by the majority of sawmill owners being from Tennessee. Criteria for chosen sawmills/lumber yards included size and operational capacity, familiarity with mass timber and CLT, and participation as suppliers in previous mass timber or CLT research projects. Familiarity with CLT and participation were verified by the investigators during the initial contacts/recruitment phase. Wood scientists, as well as engineers and architects, were located across the US with emphasis on varied expertise, field of work, and affiliations (e.g., academic vs corporate). Key informants included university professors, USDA Forest Service researchers, and private sector owners/managers of forest product companies. Familiarity, knowledge, or prior work with mass timber systems or CLT was required for both wood scientists as well as engineers and architects.

Key Informants Questionnaire

The KII questionnaire consisted of nine main interview questions with the final question left open-ended. A SWOT (strengths, weaknesses, opportunities, and threats) framework (Puyt et al. 2023) was followed to develop the questionnaire.

This framework considered both positive and negative aspects of the potential to use hardwood in CLT to better guide question generation. The list of key informant interview questions used for the interviews is listed in Table 1. The list of questions and interview protocols were reviewed and approved by the University of Tennessee Institutional Review Board for human subject research (UTK IRB-22–07110-XM). The KII checklist was used as a guideline and template for consistency across key informant interviews. Interviews were not held to a rigid time structure to allow key informants to voluntarily offer additional information according to their expertise and interest. This was done to enrich the conversation and lead to topics and aspects that may have been overlooked by the research team.

Data Analysis

Interviews were transcribed, assigned unique identifiers, and transferred into Dedoose® for analysis. Dedoose® is a program that allows for the coding and analysis of data in qualitative studies (Dedoose 2024). Transcripts were organized into the three respondent groups: wood scientists (WS), sawmill/lumber yard owners (SL), and engineer/architect (EA). Each interview was given a numerical identifier (e.g., WS1, SL2, EA6) to distinguish quotes and excerpts further on in the analysis process. Answers were coded based on subject (e.g., lumber supply, aesthetic potential, supporting infrastructure) and further coded as positive, neutral, or negative in respect to positionality on the given subject. Positive denoted confidence, hopeful, or optimistic on a given subject or aspect of hardwood CLT. Neutral positionality was denoted as having no strong positive or negative outlooks, views, or opinions. Negative positionality showed pessimistic or cynical outlooks on a given subject or aspect of hardwood CLT. Answer positionality was used for organization and to ensure differing stances on each given subject were properly represented. A code co-occurrence analysis was used to establish connections between KII answers. This was to show potential connections between given subjects and participant stances. Patterns, similarities, and comparisons between key informant groups are discussed, but no further qualitative analysis, other than the co-occurrence analysis, was performed.

Results

This section begins with the results of code co-occurrence and then presents key findings on stakeholder insights by major topics. Overall, key informants expressed optimism regarding the viability of hardwood cross-laminated timber (CLT), pointing out its favorable mechanical properties, availability of hardwood lumber, and distinct aesthetic qualities as key advantages. On the other hand, they also stressed several challenges that may hinder its broader adoption. These included the cost disadvantage of hardwood as a raw material, limited industry and consumer awareness, concerns surrounding legal liability and long-term durability (including susceptibility to biological degradation), and the absence of standardized lumber grading systems tailored to hardwood. All of these observations imply a noted deficiency in the specialized technical expertise and infrastructure necessary to support the manufacturing and structural application of hardwood CLT on a commercial scale.

Code Co-occurrences

Examining key informant co-occurring excerpts on each given topic shows insight into potentially connected topics. Interview analysis codes by number of co-occurring responses for each interview are shown in Table 2. Six code co-occurrences were the highest among all key informants. A co-occurrence with a high number indicates more key informants connected those two aspects when discussing hardwood CLT. Positive economic impact × positive environmental impact and positive hybrid potential × positive aesthetic impact were the codes that occurred most often together. For example, when asked about the economic impact of hardwood CLT, a wood scientist connected economic potential to forest and environmental health as shown below.

> *WS3: I think it would have a positive (economic) impact… we need to continually work in our forest to ensure their health. Hardwoods, in particular, are much more sustainably managed forests (compared to softwood).*

Another co-occurring pair was positive hybrid potential and positive aesthetic impact. A wood scientist discussed how hardwood could be used as a veneer to improve the aesthetics of a hybrid CLT panel with a pine core.

Table 2 Key informant codes by number of times a position on a given topic was shared with other topics in a single excerpt

Key Informant Interview Analysis Codes	Number of Co-Occurrences
Economic Impact (+) x Environmental Impact (+)	6
Hybrid Potential (+) x Aesthetic Impact (+)	6
Timber Supply (+) x Economic Impact (+)	5
Timber Supply (+) x Environmental Impact (+)	3
Technical Skills (±) x Lumber Grading (±)	3
Technical Skills (-) x Supporting Infrastructure (-)	3
Lumber Grading (+) x Mechanical Effectiveness (+)	2
Lumber Grading (-) x Technical Skills (-)	2
Timber Supply (+) x Supporting Infrastructure (+)	2
Timber Supply (+) x Price (+)	2
Technical Skills (-) x Price (-)	2
Aesthetic Impact (+) x Mechanical Effectiveness (+)	2

(+) = a positive positionality, (-) = a negative positionality, (±) = a neutral positionality

WS2: There could be an approach where the structure comes from the SYP (southern yellow pine) … If that ends up being something that can convert CLT into a more palatable aesthetic approach for a wider audience… Then maybe we have a shot at saying that these (hardwood veneer) additional layers are valuable because of that aesthetic approach.

These code co-occurrences can shed light on which aspects of hardwood in CLT were most common for key informants to share across interviews.. Inversely, given that the highest number for any co-occurrence was six, this indicates that most key informants had varying perceptions depending on the specific topic and aspect of hardwood CLT discussed.

Current Knowledge and Skill-related Barriers

A common sentiment shared by key informants was that industry professionals or the public lacked the knowledge and interest in hardwood use in CLT manufacturing. One engineer/architect informant described hardwood CLT as a niche product both currently and in terms of hardwood CLT as a future product.

EA3: Hardwood CLT is almost always talked about as a very niche product. Good in certain cases for its aesthetics, structural performance, thinness tied to structural performance… there's some happening, but it's still really niche.

It was pointed out by multiple informants that specific technical skills will be needed for the successful inclusion of hardwood in the CLT market. Questions surrounding whether hardwood lumber producers will be willing to change to new market demands were a matter of concern to engineers and architects. In particular, they questioned whether loggers and hardwood sawmills will be willing to change to new ways of cutting and processing dimensional lumber.

EA5: My question is, are they going to? They have to change something in their process. To make the input meets specs to make CLT out of it. That's like cutting trees at different cross-section dimensions to make lumber structural grade.

In contrast, some sawmill and lumber yard owners were not concerned about their industries' ability to shift to these new requirements.

SL3: It's all about what the price points are, we're willing to change... That's a new market (Hardwood CLT) for us and may improve our margins for our products.

In addition, lumber grading of hardwood for structural applications will be an important challenge for the industry. As a structurally-rated product, CLT is required to use graded lumber as a raw material. In the case of softwoods, structurally-graded lumber is the current focus of production, whereas hardwood sawmills produce lumber graded to appearance/usability standards, primarily the NHLA rules. Although structural grade rules and design values exist for many hardwood species, an engineer/architect discussed the lack of graders who are trained to structurally grade hardwood lumber and how this is a likely hurdle moving forward.

EA1: Softwood lumber graders grade for strength, while hardwood lumber graders grade for visual grade… there aren't any graders out there that can actually grade (hardwood). If you did have it in the code… there would have to be some training from Extension and workshops.

Likewise, a key informant with expertise in wood science argued that the specifics required for facilities to adjust to supply a hardwood CLT market, technical skills in particular, are a significant barrier.

WS1: A lot of these facilities do not have personnel or equipment that can actually scan or visually grade that lumber to a structural standard. So, there are barriers there, one in technology and equipment, and then human personnel.

Legal and Policy Issues

Respondents pointed out several concerns regarding the current legal provisions, particularly the building codes as they relate to the use of hardwood CLT. An engineer/architect informant shared some optimistic thoughts while also reflecting upon some complications surrounding building codes, insurance, and performance standards during one of their projects.

EA3: There's no code approved… our engineer showed his research on the structural capabilities of our Tulip poplar CLT to the code official… he said, "this is performing better than the softwood CLT that's code approved." So, they approved the material for use in our project.

An engineer/architect discussed how yellow poplar was recently added to the ANSI PRG 320 guidelines. This had already led to one company proposing the construction of a new facility in Virginia.

EA7: The PRG 320, which is the industry standard for CLT, has recently added yellow poplar… It's right now in voting… That's where the industry is at as far as having a standard. And now you have a company, TimberKraft, looking to set up the first hardwood CLT plant.

The question of how a future hardwood CLT industry will deal with liability and insurance was not a specific question asked during the key informant interview process. However, it came up several times in multiple interviews, often linked with discussions around economic feasibility and supporting infrastructure. A sawmill/lumber yard owner discussed their concerns around the liability of supplying structural-grade hardwood for use in CLT panel construction.

SL2: We do not carry any type of builder's risk or any type of product liability insurance currently… building failure, what type of liability does that create for us.... Who would be liable if that CLT failed?

This concern was also discussed by non-sawmill lumber yard owners and a wood scientist, who indicated the difficulties a hardwood CLT industry may face due to high insurance costs. They discussed the high price of insurance across the current mass timber industry.

WS5: Another issue is insurance. The insurance companies are charging outrageous amounts for construction insurance on a mass timber building… So, I'm not negative, it's still really early.

Infrastructure and Timber Resources

Supporting infrastructure will be vital in the successful use of hardwood in the CLT industry. This aspect was discussed at length by many of the key informants, and answers ranged from optimistic to pessimistic. One engineer/architect discussed the small size of hardwood sawmills and how this might bring into question the ability of a facility to get certified under the ANSI/APA PRG 320 standards.

EA7: If you're going to buy hardwoods for your CLT factory, you might be dealing with many small mills as opposed to larger ones. That will be a topic of certification because when the APA certifies a mill, like a CLT factory, a question they ask is what your resource is and how consistent will the material be coming from that resource.

A wood scientist discussed the lack of action of hardwood businesses in upgrading their systems.

WS7: I have a great chance to visit many of the sawmills... … they haven't upgraded their system, their practice, and that is making them non-competitive in the business.

Besides the supporting infrastructure (e.g., processing facility, technology), the supply of timber itself is an important aspect of any industry that relies on wood as its primary component. A wood scientist discussed the decline of hardwood-lumber-utilizing industries and how this creates an opportunity for lumber resource availability.

WS6: There's definitely a resource available for hardwoods… What's happening with hardwoods, particularly in the US, is that there's less being used. So, there's more availability of hardwoods for other purposes.

A sawmill/lumber yard owner was less optimistic about whether hardwood suppliers can keep up with demand for hardwood CLT. Capacity and how quickly hardwood can ramp up supply may be roadblocks moving forward.

SL2: We don't produce as much hardwood as we produce pine… We produce 18 million board feet a year. They (softwood producers) could be producing that weekly.

Product Characteristics

Many factors internal to the hardwood itself were pointed out by participants as strengths or weaknesses. Hardwood in CLT is in its beginning stages, and its mechanical effectiveness is still being questioned. None of the key informants had strong negative stances on mechanical effectiveness, with most optimistic to hesitantly optimistic. An engineer/architect discussed how hardwood in CLT shows potential for use in longer spans compared to softwood CLT.

EA3: For commercial use of hardwood CLT, the structural properties are important, as you can achieve longer spans for the same thickness. It's stronger and that's really important in cities... The greater we can span with the less thickness, the better hardwood CLT is than softwood CLT.

A wood scientist who had previously been involved with testing hardwood component strength properties for construction applications stated that hardwood CLT could be up to three times stronger than pine CLT.

WS1: Our results for the three hardwood species in compression: all three of those species were three times stronger than southern yellow pine… And when you look at the stiffness of the panel going from a three-ply panel to a five-ply panel, it's like three-hundred percent stronger… the hardwoods are just exponentially stronger than the pine is.

Concerns around the final cost of a hardwood CLT panel compared to other mass timber products were also pointed out by several key informants. Specifically, the cost difference between hardwood and softwood raw lumber material was brought up as a potential barrier to hardwood use. A sawmill/lumber yard owner discussed how low-grade lumber may mitigate some of this higher cost component.

SL2: Softwood is always cheaper… You're going to have to figure out a way to use low-grade hardwood… Your low-grade yellow poplar products are more in line (price-wise) with the pine product than oak…but prices even for those lower-grade poplar products are still double.

The potential for hardwood to mechanically outcompete softwood in a CLT panel was discussed as a way to add value to hardwood CLT. A wood scientist suggested that this could be achieved by requiring less material to achieve the same structural capabilities when compared to softwood CLT.

WS4: You can achieve the same mechanical properties with less volume. So that's another appealing factor of using hardwoods compared to softwoods. You can technically say that you will compensate… it costs more (by volume), but you are using less material.

In addition, utilizing both hardwood and softwood in a single CLT panel was not directly asked in the KII checklist but was brought up by many key informants. A sawmill/lumber yard owner brought up the potential of utilizing appearance grade hardwoods, such as oak, as a surface layer to increase the aesthetic appeal of a hybrid CLT panel.

SL5: You could have a combination of the two where you have a pine core, or a poplar core, but a red oak or white oak face… so that you could use it as a structural component that's actually exposed… the oaks would lend themselves better appearance wise.

In contrast, an engineer/architect who had done some work with hardwood CLT discussed some of the challenges they saw when researching previous projects that had utilized hybrid CLT panel construction.

EA3: (Referring to a previous project) Not all of them were hybrid, but some of them were hybrid and they performed very poorly. The pavilion had to be taken down well before it was due to be taken down because of delamination problems. But that was a really early-stage experiment into hybrid CLT.

However, the same engineer/architect then went on to discuss the positive potential for hybrid CLT.

EA3: What our team discovered in many different types of hardwood/softwood layups was that they performed very well structurally. It was about the process, the glues used, and the science of it, which wasn't done properly in the Columbus project.

Longevity and decay were discussed during key informant interviews, with fire, moisture, and pest resistance being common aspects. These aspects were often correlated and discussed alongside those of softwood CLT. A wood scientist summarized the potential struggles hardwood CLT may face as far as decay and longevity are concerned.

WS3: You're going to have to figure out how to make it fire resistant, mold resistant, and also get that high appearance out of it… You look at the cross-laminated timber manual... there's not a single chapter on wood durability, that's an issue… It's important that we continually monitor and ensure the structural integrity of these hardwood CLT buildings.

Key informants were generally positive about fire resistance when discussing hardwood CLT and the currently in-use softwood CLT products. A wood scientist who had done testing on wood element burn rates was positive about hardwood CLT's fire resistance. They argued that a hardwood structure likely has a more predictable fire resistance than that of concrete due to wood's innate and predictable fire resistance.

WS5: I am pretty optimistic. Why? Because concrete fails quickly in high heat... If I put a mass timber product, and there is a fire burning, it will take a long time to burn. And it will burn at a predictable rate... I can design a two-

hour fire-resistant building… and within two hours, I can get a person out of a building.

Outside of mechanical or physical properties, hardwood overall was stated as an aesthetically pleasing material by key informants. The degree to which aesthetics play into the equation of hardwood CLT acceptance and market viability was the primary focus in these discussions. A positive response from a wood scientist discussed his optimistic outlook surrounding hardwood aesthetics and human perception of built environments.

WS1: I've seen some really interesting studies over the years with biophilic properties and how we respond to that. If you look at a hospital setting, or an office setting, there's been a good bit of work on people's moods and feelings and how they respond positively in a wood environment.

An engineer/architect discussed the importance of aesthetics to architects and end users and how hardwood may play a positive role in these equations.

EA4: For architects, end users, specifiers, the aesthetics are always going to be really huge. I definitely think if there is an aesthetic sell, that will be really large.

Economic Impact

Key informants were generally positive when considering the potential economic opportunities in establishing a hardwood CLT market. An engineer/architect raised the potential of a hardwood CLT facility to benefit rural economies.

EA3: We can utilize rural facilities that may have been abandoned or underused to house new equipment and train a new workforce to generate a new economic base... It's something of high value that rural economies in particular can market.

A sawmill/lumber yard owner discussed the value in having a local wood processor.

SL3: I think it would be good. Lots of our communities are pretty distressed; it could add jobs in the community... We're always looking for another supplier for our product… we'd rather ship it locally and make a product domestically.

Future Steps and Recommendations

Key informants were asked to give their opinion on recommendations for the manufacturing and promotion of hardwood in CLT. Key informants questioned the viability of subsidies and how they may have a negative impact as far as long-term market health is concerned.

EA1: Subsidies are always helpful, but I think it's going to have to be self-sustaining… subsidies are very helpful in getting things started, but then if subsidies are given and there's no profitability after the subsidies go away, then it's not really a good strategy.

An engineer/architect discussed the importance of education for the owners, architects, and engineers.

EA6: Education is a big deal with this new technology. Educating the owners, the architects, the engineers.

An engineer/architect discussed the importance of demonstrating the successful use of low-value hardwood to help reinforce the lessons learned from research.

EA3: It's important for our region to maximize the use of our low-value forest resources… There needs to be more demonstration for one, because I think the research is there proving that structurally it works… We need to test this out in the real world to verify performance.

Discussion

Barriers for Hardwood CLT

Barriers for hardwood CLT varied from concerns about cost, timber supply, and demand, to a lack of technical and grading skills. The Code Co-occurrence analysis showed that technical skills × supporting infrastructure, lumber grading × technical skills, and technical skills × price were the most often negative connections made by key informants. Statements connecting negative positions on technical skills and supporting infrastructure were the most common. This is likely due to both the lack of technical skills and supporting infrastructure being major barriers stated by key informants. Negative positions on lumber grading and price being connected to technical skills likely fall under the same reasoning as supporting infrastructure. The code connection between negative positions on aspects of hardwood CLT means that key informants were most likely to share positionality on multiple different aspects of hardwood CLT. These negative co-occurrences were less common across all key informants, likely indicating that barriers are less agreed upon than opportunities. Given that the highest negative co-occurrence was three, this indicates that the majority of key informants did not share multiple negative opinions with other key informants. Some insight can be gained by examining the few instances of negative co-occurrences, however, these results should not be given too much weight when discussing barriers for hardwood CLT.

The high cost of lumber will likely remain one of the larger barriers to hardwood usage in CLT. This was generally an agreed-upon position across all key informants. Lower-cost hardwoods were discussed by several key informants, but no definitive answers or solutions were agreed upon. Another potential to lower the cost while keeping the aesthetics of hardwood is in the manufacture of hybrid hardwood and softwood CLT panels (Kramer et al. 2014; Aicher et al. 2016; Brunetti et al. 2020; Sciomenta et al. 2021). Discussion among key informants was generally optimistic about hybrid CLT, with several stating this as the best way to lower costs while retaining the visual component of hardwood.

The lack of structural lumber grading, lack of technical skills, and supporting infrastructure wasoften discussed at length by key informants as high barriers for hardwood in CLT. Most key informants agreed on these barriers, with only a few stating them to be minor or non-concerning barriers. These barriers focus primarily on hardwood lumber producers as well as the infrastructure to transport sawn lumber. Specifics included:

- Structural grading is currently not done at hardwood sawmills, as hardwood lumber is graded for visual appearance and non-structural purposes (Cassens 2001). Once a hardwood species (e.g., yellow poplar) is added to structural guidelines, sawmills will then need to train and/or hire new personnel who possess the expertise to structurally grade this lumber
- Common methods for drying hardwood lumber can take weeks to months (Stelzer 2017, Hiziroglu & Hitch 2017), whereas softwood structural lumber is routinely dried within a few days.
- Hardwood lumber is cut into random lengths (sometimes) and random widths (usually), leading to the need to re-cut and trim lumber before inclusion in CLT and the loss of valuable lumber (Espinoza & Buehlmann 2018; Adhikari et al. 2020).

All of these factors make sourcing hardwood lumber for CLT more challenging. Key informants felt that these barriers could be overcome, given time and sufficient sustained demand. It is also of note that these barriers are not novel to hardwood CLT, with softwood CLT needing to overcome similar barriers previously.

Other barriers such as liability and insurance, decay and longevity, and fire safety were aspects brought up by key informants. Liability and insurance and decay and longevity were generally agreed upon barriers across key informants. Fire safety varied, with some key informants stating it as a major barrier, while others held the position that it was minor and easily overcome. A handful of studies have performed fire performance on softwood CLT and found positive results (Harte 2017; Abed et al. 2022). Although these studies were optimistic about softwood CLT's fire resistance, more studies will be needed to establish if hardwood CLT shows the same fire resistance as softwood CLT. No studies have been done thus far on liability, insurance, decay, or longevity specifically related to hardwood CLT panels, and these topics may be equally applicable to the development of a softwood-based CLT industry. Many questions surrounding CLT decay and longevity are still unanswered, and further research is needed (Cappellazzi et al. 2020; Udele et al. 2021). When examining liability and insurance concerns, correlations can be made by looking at the softwood CLT industry. WoodWorks (2024a, b) stated that the two insurance challenges facing mass timber are builder's risk insurance and fixed property insurance. These insurances cover risks for builders and property owners. This need for insurance by the lumber suppliers was not pointed out, but it was a common concern expressed by the key informants among the sawmill and lumber yard owners' group in the current study. These barriers are likely not novel to hardwood CLT, and many of these aspects have been addressed in other closely related industries such as softwood CLT.

Opportunities for Hardwood CLT

Key informants tended to feel that although hardwood inclusion in CLT will likely not be a complete solution for declining hardwood markets, any new economic growth would be a positive. Additionally, the key informants felt that a growing hardwood CLT market would not negatively impact current forest resources, which is consistent with research findings (Comnick et al. 2021; Nepal et al. 2021, 2024; Pasternack et al. 2022). The interviewed sawmill and lumber yard owners often expressed confidence that their industry could adequately supply a growing hardwood CLT market.

The Code Co-occurrence analysis shows what aspects of hardwood CLT key informants are likely to consider connected. These variables show potential to have either connected solutions, problems, or compounded positive or negative effects. If a key informant stated that hardwood CLT will have a positive economic impact for example, then they were likely to believe that it will have positive environmental impacts as well. Key informants connected a positive economic impact to positive environmental implications. This could be due to the potential of hardwood CLT and carbon storage and its perceived economic benefits, or due to a general view that hardwood CLT will have both positive economic and environmental impacts. This analysis did not discover with certainty why positive economic and environmental impacts were so frequently connected. The questions asked of key informants for this study were not specific enough, leading to potential for a future study to better define why more key informants believe both the positive economic potential and positive environmental potential of hardwood CLT. The same number of key informants connected positive hybrid potential and positive aesthetic impact. This connection was more clearly stated by key informants when compared to positive economic and environmental impacts. Implementing veneer lamination of hardwood onto the outside of a softwood CLT panel was the most common answer for why positive hybrid and aesthetic aspects were connected. Similar to positive hybrid and aesthetic aspects, positive timber supply and economic impacts were easier to definitively establish across key informants. The most common sentiment was that hardwood CLT shows potential to revitalize struggling timber markets, leading to more economic growth.

Most key informants in this study were optimistic about the mechanical performance of hardwood CLT, with only a few stating hesitancies or minor concerns. Some key informants even stated that they saw potential for hardwood CLT to outperform softwood CLT in certain scenarios. This is consistent with literature on the testing of hardwood CLT, in which most researchers have concluded that hardwood CLT, including that made from low-grade lumber, performs sufficiently for structural applications (Ehrhart & Brandner 2018; Crovella et al. 2019; Abdoli et al.

2022; Azambuja et al. 2022; Palacio-Betancur et al. 2023). It is of note that softwood CLT had to overcome similar aspects during its development, and it will likely only require further research and time for hardwood CLT to definitely establish its mechanical effectiveness.

Connected to mechanical effectiveness and performance is the question of code acceptance. Key informants generally agreed that these aspects are major barriers and will require time and effort to address. The use of new species in CLT, such as various hardwoods available in the United States, requires their inclusion in the ANSI/APA PRG 320 standards for mass timber products (APA 2020). Yellow poplar has been qualified under the most recent iteration of the PRG 320, according to a key informant involved in the process. Yellow poplar is readily available in most hardwood markets in sufficient quantities, a likely reason it was the first to be tested for acceptance under the PRG 320 guidelines. Given the positive testing results for other hardwood species (Ehrhart & Brandner 2018; Crovella et al. 2019; Abdoli et al. 2022; Palacio-Betancur et al. 2023), it is likely that more hardwood species could pass the PRG 320 testing process. Testing and code development are still in the early stages, and it will likely take years of continued research to determine the most promising species for CLT manufacturing. Softwood CLT also had to go through similar hurdles and barriers surrounding code development, and it will likely require time for codes to develop surrounding hardwood CLT.

Aesthetics and hybrid potential are often interconnected aspects associated with hardwood inclusion in CLT. Although most key informants were positive about the aesthetic aspects, they had mixed positions when discussing hybrid potential. Some key informants stated hybrid potential as one of the largest selling points of hardwood CLT, while others were less optimistic. Overall, key informants in this study indicated aesthetic beauty and appearance of hardwoods in CLT will be an important aspect. This aesthetic value may be one of hardwood CLT's strongest selling points. In addition, the discussion around the potential of hybrid CLT panel construction implied that utilizing both softwood and hardwood lumber may achieve these aesthetic values while keeping costs low. This would involve either applying a hardwood veneer to a softwood CLT panel or replacing the outer layer(s) of a softwood CLT panel with hardwood lumber. Scientific testing into hybrid CLT panel construction has been optimistic, with some researchers finding greater mechanical effectiveness when compared to softwood CLT panels (Aicher et al. 2016; Brunetti et al. 2020; Sciomenta et al. 2021). This is likely a valuable area for new research to be conducted, as the financial and aesthetic value-adding components show promise. If wholly hardwood CLT does not succeed in the larger mass timber and CLT markets, hybrid panels may still succeed.

Even though this study was focused on hardwood and respondents were not asked to compare it against softwood, emerging literature on wood science and survey-based studies imply that some of the challenges or barriers identified by the key informants in the current study are not necessarily unique to hardwoods. For example, familiarity with CLT and associated technical skills was found low among the stakeholders of predominantly softwood regions of the US South (Vloskey et al. 2019) and the awareness and willingness of CLT adoption in end use was found to be very limited among the engineers and developers across the nation (Laguarda-Mallo and Espinoza 2015; 2018). In addition, the issues of liability and insurance as perceived barriers, along with fire resilience and economic benefits as strengths, are also not associated with hardwood CLT only but are rather equally applicable in softwood. However, considering that the market for traditional forest products (e.g., pulp, newsprint) that has long utilized hardwood biomass is declining in many hardwood regions (Poudyal et al. 2017) and the nationwide export of hardwood has also declined recently (NHLA 2024), utilizing hardwood for CLT may generate larger marginal benefit to regional economies impacted by such decline.

Nonetheless, the general lack of experience in using hardwoods in structural applications, relatively small scale and diversity of the hardwood industry, challenge of sustainable timber supply (mainly in right size and dimensions) (Adhikari et al. 2020), and low price competitiveness (Hassler et al. 2024) of hardwood compared to softwood are unique disadvantages to the promotion of hardwood CLT. On the other hand, the prospect of using it in a hybrid panel for structural or aesthetic appeal in interior structures (Chen et al. 2025), alongside the potential of its production being an alternative economic engine for rural communities in hardwood regions impacted by recent closure of traditional forest product companies, are unique aspects of hardwood CLT that justify investment in hardwood CLT production.

Conclusions

Key informants in the wood products industry who were interviewed in this study are generally positive about the potential for including hardwood in CLT. Key informants were chosen due to their previous work, research, or expertise surrounding hardwood CLT and may be more optimistic when compared to the larger industry as a whole. While many of the findings reported in this study were also presented in non-social science literature on CLT (e.g., Espinoza & Buehlmann 2018), findings from this perception-based study of the informed stakeholders in the industry reinforce conclusions and indicate convergent validity of the findings reported in emerging literature on wood science of hardwood CLT. Widespread adoption of a product like hardwood CLT needs stakeholder buy-in; therefore, these new findings regarding perceptions and attitudes among stakeholders can be valuable in informing more targeted, impactful strategies for adoption and promotional communication within the industry. The code co-occurrence results are particularly valuable as they give insight into what aspects of hardwood CLT stakeholders feel are most connected. This can help target areas of promotion and help us better communicate the opportunities and barriers of hardwood CLT. The similarity in findings from the current perception-based study with those reported previously in wood science literature is a notable finding because the industry perceptions regarding hardwood CLT are generally in line with the findings reported in scientific literature. Any gap between these would have called for investing in education and outreach to inform the industry on the scientific findings. Aligned stakeholder perception with the product's actual strengths and weaknesses helps manage expectations, fosters credibility, and creates a solid foundation for initial adoption and sustained business.

In addition, by presenting the additional perspectives from knowledgeable stakeholders in the industry, findings also shed light on the suitability of potential policy measures (e.g., providing subsidies) promoting hardwood CLT and suggested areas of research needs (e.g., hybrid panels). Key informants emphasized that the more promising areas for hardwood CLT are its mechanical effectiveness, potential to alleviate struggling markets, and positive aesthetic attributes. Key informants generally suggested that educating the public about the potential benefits (e.g., aesthetic, durability, economic benefit) of hardwood CLT products over traditional products has the potential to enhance hardwood CLT's marketability and perception. These promising areas are further showcased with the results of the code co-occurrence study. These co-occurrences show what aspects of hardwood CLT stakeholders are likely to agree upon. Although key informants were generally positive, they also identified potential barriers that likely remain for hardwood in CLT. These include high cost of raw lumber material, limited awareness, lack of hardwood structural grading, and limited relevant technical skill in the industry. The Code co-occurrence analysis showed that several aspects of hardwood CLT are likely connected in both positive and negative ways. Although it is difficult to state definitive results on positionality, these results can help inform future research and what areas of hardwood CLT are likely interconnected. Key informants were generally optimistic about these barriers and implied that many would be overcome given time, research, and sufficient market demand. Key informants were generally hesitant when discussing subsidies as a general solution. The recent addition of yellow poplar to the ANSI/APA PRG 320 guidelines has marked a pivotal first step for hardwood in CLT. While hardwood in CLT offers potential to add novel use for hardwood lumber, it is likely that hardwood in CLT will be only a niche component of the greater mass timber market.

Author Contribution Bremner (study design, data collection and analysis, writing of first draft); Poudyal (study design, analysis, funding acquisition, supervision, writing of first draft, review and editing); Nepal (review and editing); Brandeis (review and editing); Taylor (review and editing).

Funding Funding support from the USDA Forest Service, Southern Research Station (CR#21-CR-11330145–068) and USDA Forest Service, Forest Products Laboratory (JV# 21-JV-11111137–018) and University of Tennessee, School of Natural Resources is acknowledged.

Data Availability Data used in this study area obtained from individuals with assurance of confidentiality and therefore not available for wide sharing.

The qualitative interview data used in this study were obtained from individual research participants with the assurance of confidentiality and therefore cannot be shared.

Declarations

Ethics Approval The list of questions and interview protocols were reviewed and approved by the University of Tennessee Institutional Review Board for human subject research (UTK IRB-22–07110-XM).

Consent to Participate Consent of research participants was obtained before the interview began, according to the protocol approved by UTK IRB office.

Competing interests Authors declare no competing interest regarding this study.

References

Abdoli, F., M. Rashidi, R.-H. Akbar, L. Mohammad, and E. Ghanbar. 2022. Withdrawal performance of nails and screws in cross-laminated timber (CLT) made of poplar (Populus Alba) and Fir (Abies Alba). *Polymers* 14 (15): 3129. https://doi.org/10.3390/polym14153129.

Abed, J., S. Rayburg, J. Rodwell, and M. Neave. 2022. A review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures. *MDPI Sustainability (Basel Switzerland)* 14 (9): 5570. https://doi.org/10.3390/su14095570.

Adhikari, S., H. Quesada., B. Bond., and T. Hammett. 2020. "Potential of hardwood lumber in cross laminated timber in North America: A CLT manufacturer's perspective" Mass Timber Construction Journal 3(1), 1–9. Accessed October 14, 2023. https://www.journalmtc.com/index.php/mtcj/article/view/20

Aicher, S., M. Hirsch, and Z. Christian. 2016. Hybrid cross-laminated timber plates with beech wood cross-layers. *Construction & Building Materials* 124:1007–1018. https://doi.org/10.1016/j.conbuildmat.2016.08.051.

Anderson, R., E. Dawson., D. Atkins., L. Muszynski. 2024. "International mass timber report 2024" Trifecta Collective LLC. Arlington, VA. Pg. 334. Accessed March 15 2024. https://www.masstimberreport.com/.

APA. 2020. PRG 320–2019ANSI/APA PRG 320–2019. "Standard for performance-rated cross-laminated timber" APA-The engineered wood association. Tacoma, WA. Accessed March 15, 2024. https://www.apawood.org/publication-search?q=PRG+320&tid=1.

Bergman, R., W. T. Simpson, and C. Turk. 2010. Evaluating warp of 2 by 4s sawn from panels produced through green gluing dimension lumber from small ponderosa pine logs. *Forest Products Journal* 60 (1): 57–63.

Brandeis, C., M. Taylor., K. L. Abt., D. Alderman., and U. Buehlmann. 2021. Status and trends for the U.S. forest products sector: a technical document supporting the USDA Forest Service 2020 RPA assessment. Gen. Tech. Rep. SRS 258. Asheville, NC: USDA Forest Service, Southern Research Station. https://doi.org/10.2737/SRS-GTR-258.

Brashaw, B., and R. Bergman. 2021. Chapter 1: Wood as a renewable and sustainable resource. In *Wood handbook—wood as an engineering material*. *General technical report FPL-GTR-282*, 17. Madison: USDA Forest Service, forest products laboratory. https://www.fs.usda.gov/research/treesearch/62241.

Brunetti, M. Nocetti, B. Pizzo, F. Negro, G. Aminti, P. Burato, C. Cremonini, and R. Zanuttini. 2020. Comparison of different bonding parameters in the production of beech and combined beech-spruce CLT by standard and optimized tests methods. *Construction & Building Materials* 265:120168. https://doi.org/10.1016/j.conbuildmat.2020.120168.

Cai, Z., C.A. Senalik., and R.J. Ross. 2021. Chapter 12: mechanical properties of wood based composite materials. In *Wood handbook—wood as an engineering material*. *General technical report FPL-GTR-282*, 15. Madison, WI: USDA Forest Service, forest products laboratory.

Cappellazzi, J., M. J. Konkler, A. Sinha, and J. Morrell. 2020. Potential for decay in mass timber elements: a review of the risks and identifying possible solutions. *Wood Material Science and Engineering* 15 (6): 351–360. https://doi.org/10.1080/17480272.2020.1720804.

Cassens, D. L. 2001. "Quality control in lumber purchasing: hardwood lumber grades" Forestry and natural resources, Purdue University.Accessed June 6, 2024. https://www.extension.purdue.edu/extmedia/fnr/fnr-130.pdf

Chen, C., J. Mo. Haviarova. 2025."Adding value to hardwoods- thin hardwood cross-laminated timber (HCLT)". Wood Material Science & Engineering. https://doi.org/10.1080/17480272.2025.2457558

Comnick, J., L. Rogers, and K. Wheiler. 2021. Increasing mass timber consumption in the U.S. and sustainable timber supply. *MDPI Sustainability* 14 (1): 381. https://doi.org/10.3390/su14010381.

Crabtree, B. F., W. L. Miller., L. William. 1999. "Doing Qualitative Research" 2nd ed. Sage Publications

Crovella, P., W. Smith, and J. Bartczak. 2019. Experimental verification of shear analogy approach to predict bending stiffness for softwood and hardwood cross-laminated timber panels. *Construction & Building Materials* 229:116895. https://doi.org/10.1016/j.conbuildmat.2019.116895.

da Azambuja, R. R., D. B. DeVallance, and J. McNeel. 2022. Evaluation of low-grade yellow-poplar (*Liriodendron tulipifera)* as raw material for cross-laminated timber panel production. *Forest Products Journal* 72 (1): 1–10.

Dedoose. 2024. “cloud application for managing, analyzing, and presenting qualitative and mixed method research data” Los Angeles, CA: sociocultural research consultants, LLC. Version 9.2.012. www.dedoose.com.

Ehrhart, T., and R. Brandner. 2018. Rolling shear: test configurations and properties of some European soft- and hardwood species. *Engineering Structures* 172:554–572. https://doi.org/10.1016/j.engstruct.2018.05.118.

Elmendorf, W., and A. E. Luloff. 2006. Using Key Informant Interviews to Better Understand Open Space Conservation in a Developing Watershed. *Arboriculture & Urban Forestry* 32 (2): 54–61. https://doi.org/10.48044/jauf.2006.007.

Espinoza, O., and U. Buehlmann. 2018. Cross-laminated timber in the USA: opportunity for hardwoods? *Current Forestry Reports* 4 (1): 1–12. https://doi.org/10.1007/s40725-018-0071-x.

Ettelaei, A., A. Taoum, J. Shanks, and G. Nolan. 2022. Rolling shear properties of cross-laminated timber made from Australian plantation eucalyptus nitens under planar shear test. *Forests* 13 (1): 84. https://doi.org/10.3390/f13010084.

Harpole, G. B., Williston, E., and Hallock, H. H. 1979. Investment opportunity: the FPL EGAR lumber manufacturing system. Res. Paper FPL-310. Madison: USDA Forest Service, Forest Products Laboratory

Harte, A. M. 2017. Mass timber - the emergence of a modern construction material. *Journal of Structural Integrity and Maintenance* 2 (3): 121–132. https://doi.org/10.1080/24705314.2017.1354156.

Hassler, C. C., M. Young, L. Denes, B. Bencsik, and J. F. McNeel. 2024. An Evaluation of Low-Grade Red Oak and Soft Maple as Raw Material for Cross-Laminated Timber Panel Production. *Forest Products Journal* 74 (2): 107–120. https://doi.org/10.13073/FPJ-D-23-00058.

Hiziroglu, S., K. Hitch. 2017. “Practicalities in Air-Drying Lumber” OSU Extension. Accessed May 5, 2024. https://extension.okstate.edu/fact-sheets/practicalities-in-air-drying-lumber.html

Junnila, S., and A. Horvath. 2003. Life-cycle environmental effects of an office building. *Journal of Infrastructure Systems* 9 (4): 157–166. https://doi.org/10.1061/(ASCE)1076-0342(2003)9:4(157).

Kramer, A., A. R. Barbosa, and A. Sinha. 2014. Viability of hybrid poplar in ANSI approved cross-laminated timber applications. *Journal of Materials in Civil Engineering* 26 (7): 06014009. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000936.

Kumar, V., M. Lo Ricco, R. D. Bergman, P. Nepal, and N. C. Poudyal. 2024. Environmental impact assessment of mass timber, structural steel, and reinforced concrete buildings based on the 2021 international building code provisions. *Building and Environment* 251:111195.

Laguarda-Mallo, M. F. L., and O. Espinoza. 2015. Awareness, perceptions and willingness to adopt cross-laminated timber by the architecture community in the United States. *Journal of Cleaner Production* 94:198–210.

Laguarda-Mallo, M. F. L., and O. Espinoza. 2018. Awareness, perceptions and willingness to adopt cross-laminated timber by U.S. engineering firms. *BioProducts Business* 3 (1): 1–14.

Liao, Y., D. Tu, J. Zhou, H. Zhou, H. Yun, J. Gu, and C. Hu. 2017. Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers. *Construction & Building Materials* 132:508–515. https://doi.org/10.1016/j.conbuildmat.2016.12.027.

Nepal, P., C. M. T. Johnston, and I. Ganguly. 2021. Effects on global forests and wood product markets of increased demand for mass timber. *Sustainability* 13 (23): 13943. https://doi.org/10.3390/su132413943.

Nepal, P., J. P. Prestemon, I. Ganguly, V. Kumar, R. D. Bergman, and N. C. Poudyal. 2024. The potential use of mass timber in mid-to high-rise construction and the associated carbon benefits in the United States. *PLOS ONE* 19:e0298379. https://doi.org/10.1371/journal.pone.0298379.

NHLA, 2023. “Lumber & Products Members”. The National Hardwood Lumber Association. Accessed May 15, 2023. https://members.nhla.com/eweb/DynamicPage.aspx?WebCode=MbrDirLumber&orderby=state&dir=A

NHLA. 2024. “Exports Remain Vital to the US Hardwood Industry, but Challenges and Uncertainty Around the Globe Continue to Grow.” https://nhla.com/news/exports-remain-vital-to-the-us-hardwood-industry-but-challenges-and-uncertainty-around-the-globe-continue-to-grow/

Palacio-Betancur, A., S. J. Hormozabad, C. Niman, P. Masterson, B. Sturlaugson, J. Brewer, B. Swetnam, L. S. Bryson, and M. G. Soto. 2023. Compressive properties of cross-laminated timber panels made of hardwood tree species from the Appalachian Region. *Journal of Architectural Engineering* 29 (1): 04022043. https://doi.org/10.1061/JAEIED.AEENG-1441.

Parajuli, R., F. Laleicke. 2018. “Mass timber products: innovative wood-based building materials” NC State Extension. Accessed May 2, 2024. https://content.ces.ncsu.edu/mass-timber-products-innovative-wood-based-building-materials

Pasternack, R., M. Wishnie, C. Clarke, Y. Wang, E. Belair, S. Marshall, H. Gu, P. Nepal, F. Dolezal, G. Lomax, C. Johnston, G. Felmer, R. Morales-Vera, M. Puettmann, and R. Van den Huevel. 2022. What Is the impact of mass timber utilization on climate and forests? *Sustainability* 14 (2): 758. https://doi.org/10.3390/su14020758.

Puyt, R. W., F. B. Lie, and C. P. M. Wilderom. 2023. The origins of SWOT analysis. *Long Range Planning* 56 (3): 102304.

Saunders, B., J. Sim, T. Kingstone, S. Baker, J. Waterfield, B. Bartlam, H. Burroughs, and C. Jinks. 2018. Saturation in qualitative research: exploring its conceptualization and operationalization. *Quality & Quantity* 52 (4): 1893–1907. https://doi.org/10.1007/s11135-017-0574-8.

Schenk, M., H. Clara, and M. C. José. 2022. Cross-laminated timber: a survey on design methods and concepts in practice. *CivilEng* 3 (3): 610–629. https://doi.org/10.3390/civileng3030036.

Sciomenta, M., L. Spera, C. Bedon, V. Rinaldi, M. Fragiacomo, and M. Romagnoli. 2021. Mechanical characterization of novel homogeneous beech and hybrid beech-corsican pine thin cross-laminated timber panels. *Construction & Building Materials* 271:121589. https://doi.org/10.1016/j.conbuildmat.2020.121589.

SkyCiv Industry 2021. “Everything You Need to Know about Cross Laminated Timber” Accessed October 1, 2024. https://skyciv.com/industry/cross-laminated-timber-clt/

Stelzer, H. 2017. “Air-Drying Hardwood Lumber” *U of M Extension*. Accessed May 5, 2024. https://extension.missouri.edu/publications/g5550#:~:text=Air%2Ddrying%20and%20solar%20kiln,construction%20uses%20and%20exterior%20applications.

Timber Update. 2023. “Current Timber Prices: All Timber Prices | Q1 2023”. Accessed December 6, 2023. https://timberupdate.com/timber-prices/

Twongyirwe, R., M. Bithell, and K. S. Richards. 2018. Revisiting the drivers of deforestation in the tropics: insights from local and key informant perceptions in Western Uganda. *Journal of Rural Studies* 63:105–119. https://doi.org/10.1016/j.jrurstud.2018.08.013.

Udele, K. E., J. J. Morrell, and A. Sinha. 2021. Biological durability of cross-laminated timber- the state of things. *Forest Products Journal* 71 (2): 124–132. https://doi.org/10.13073/FPJ-D-20-00076.

Vlosky, R. P., R. Parajuli, F. Laleicke, and M. T. LeBlanc. 2019a. CLT study: Encouraging results. *Forest Landowner* July/August:25–26.

Vlosky, R. P., R. Parajuli., M. T. LeBlanc., C. B. Gale. 2019b. “Influencer perceptions of cross-laminated timber in the U.S. South” Digitalization and circular economy: forestry and forestry-based industry implications

Walch, F., R. Watts. 1923. “Composite lumber” US Patent 1,465,383. Accessed May 5, 2024. https://patents.google.com/patent/US1465383A/en

WoodWorks, 2024a. “Building insurance for mass timber” Accessed May 15, 2024. https://www.woodworks.org/learn/mass-timber-clt/mass-timber-building-insurance/

WoodWorks, 2024b. “Building Trends: Mapping Mass Timber” Accessed July 23, 2024. https://www.woodworks.org/resources/mapping-mass-timber/#:~:text=In%20the%20U.S.%2C%202%2C205%20multi,projects%20from%20design%20to%20completion.

Yadav, R., and J. Kumar. 2021. Engineered wood products as a sustainable construction material: a review. *IntechOpen*. https://doi.org/10.5772/intechopen.99597.

Authors and Affiliations

Alexander Bremner[1] · **Neelam Chandra Poudyal**[1] · **Prakash Nepal**[2] · **Consuelo Brandeis**[3] · **Adam Taylor**[1]

✉ Neelam Chandra Poudyal
npoudyal@utk.edu

[1] School of Natural Resources, University of Tennessee, Knoxville, TN, USA

[2] USDA Forest Service Forest Products Laboratory, Madison, WI, USA

[3] USDA Forest Service Southern Research Station, Knoxville, TN, USA