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REVIEW ARTICLE

Laminated strand lumber (LSL) potential of Hungarian and Central European hardwoods: a review

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Abstract

This review paper discusses the potential of laminated strand lumber (LSL) as a structural and building material, with a focus on Hungarian hardwoods such as Turkey oak, hornbeam, beech, and domestic poplar. LSL is an engineered wood product made from thin strands of wood that are glued together in layers. The study compares the physical and mechanical properties of LSL made from these hardwood species with those of other conventional structural materials. In addition, the paper discusses various aspects of LSL such as thermal, morphological, and durability, to provide a comprehensive analysis of the LSL material. Furthermore, a SWOT (strengths, weaknesses, opportunities, and threats) analysis is conducted to understand the strengths and weaknesses of LSL products. This analysis sheds light on the pros and cons of utilizing LSL crafted from certain hardwoods and provides suggestions for improving their performance in various settings. Overall, the report demonstrates the potential of utilizing LSL made from these particular hardwood species and offers recommendations for future studies to benefit LSL manufacturers and researchers significantly.

1 Introduction

The search for eco-friendly and long-lasting substitutes for conventional lumber has gained momentum in recent years. Laminated strand lumber (LSL) is also known as a composite material which is created by bonding fibrous wood strands together using adhesives. Because of its high strength-to-weight ratio and ready availability from renewable resources, LSL has emerged as a potentially useful alternative. Traditionally, some engineered wood products like LVL are primarily derived from softwoods such as Scots pine (Aro et al.2017). However, there is a growing interest in utilizing hardwoods for LVL production as well. Nevertheless, it is necessary to understand the usage of different wood species and their qualities in order to fully explore the potential of LSL. Currently, an ongoing project is underway at the University of Sopron in Hungary, focusing on "The Role of Forest-Based Bioeconomy in Climate Change Mitigation through Carbon Storage and Material Substitution" (Commission 2021). This project is funded by the European Union and aims to investigate various wood species to discover innovative methods of reducing the greenhouse effect in the environment. Moreover, in addition to various other products, LSL has emerged as a significant area of investigation to explore innovative approaches for safeguarding the environment by substituting conventional non-biodegradable structural materials.

LSL incorporates wood strands, regardless of quality or wood defects, in order to be leveraged effectively. This is typically considered as an extension of OSB (oriented strand board). However, LSL strands have a length of 12 inches (304.8 mm), which is longer than the strands utilized in the production of OSB. LSL typically does not exhibit distinct cervical shapes or staining, which makes it highly suitable for structural framing. In comparison to PSL, glulam, and LVL, LSL exhibits lower shear strength, which makes it more favorable for shorter frames (SFS Group USA, 2023). Due to its exceptional strength, durability, and affordability, LSL has emerged as a highly promising product, rapidly gaining popularity within the construction industry. LSL is crafted by compressing thin strips of wood with a resin

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binder, resulting in the formation of a sturdy lumber with substantial thickness (Liu et al. 2008). This manufacturing process yields a consistently robust and uniform material, making it ideal for a wide range of building applications such as framing, beams, and columns (Asdrubali et al. 2017).

Structural Composite Lumber (SCL) is a form of engineered wood product that contains a variety of composite materials developed for structural uses. It includes, among other things, LSL, LVL, and PSL (Parallel Strand Lumber). These products are made by gluing wood strands, veneers, or fibers together using adhesives under regulated conditions that produce strong, homogeneous, and dimensionally stable structural components. LSL was created expressly as a member of the SCL family to provide an alternative to solid sawn timber. The primary purpose was to overcome some of traditional lumber's shortcomings, including a possible variation in strength, stiffness, and dimensional stability. LSL strives to increase structural performance and uniformity by adopting engineered wood production processes. LSL's versatility stems, in part, from the fact that it may be fabricated from many different kinds of wood including both soft and hardwood. In Hungary, wood species including Turkey oak, hornbeam, beech, and domestic poplars show the greatest promise for LSL manufacture because of their high stiffness, strength, and dimensional stability, among other desirable mechanical attributes (Monlar Sandor 2002). Furthermore, these species are plentiful and easily accessible across a wide range of geographic areas including Hungary and other European countries (Monlar Sandor 2002), making them a sustainable and cost-effective choice for LSL production.

There is a dearth of thorough knowledge and study on the appropriateness of certain wood species for use in LSL manufacturing, despite the advantages that may be gained from doing so. By reviewing and assessing the current literature on the mechanical qualities, processing techniques, and performance in LSL applications of Hungarian Turkey oak, hornbeam, beech, and domestic poplars, this study hopes to investigate the possibilities of employing these woods in LSL applications. To understand the potential of various wood species better for LSL production and to influence future development and optimization of LSL materials, this study will also emphasize the significant difficulties and possibilities for additional research in this field.

2 Classification of woods

Wood is a prominent naturally derived lignocellulosic material which is found significantly in nature (Jakob et al. 2022). Generally, there are two primary ways to categorise temperate wood species: softwoods and hardwoods (de Almeida et al. 2021). Softwoods are used for wood-based products since long time. Coniferous trees are the source of softwoods, which find widespread usage in framing, decking, and roofing. Pine, fir, spruce, and cedar are some of the examples of typical softwoods which have widespread application in the construction industry. Another type of widely available wood category is the hardwoods. Typically, strong, dense, and long-lasting, hardwoods are harvested from deciduous trees. However, previously they were not studied significantly for wood-based products development. Nowadays, hardwoods are getting popularity for use in a variety of woodworking projects. Oak, maple, walnut, and cherry are all examples of hardwoods. Moreover, wood can be further subdivided into grades based on quality and attributes within each of these groups (Jakob et al. 2022). In North America, for instance, hardwoods are graded according to criteria such as the number and extent of defects, the colour and grain pattern, and the overall quality specified by the National Hardwood Lumber Association (Council 2017; Walker et al. 2006). The American Softwood Timber Standard establishes similar grading criteria for softwood timber, including its strength and rigidity, the amount and shape of knots, and its general appearance. Europe has a series of harmonized standards for the strength classification of wood, based on either visual characteristics or instrumental stress grading (Institute 2016b). Hardwood and softwood stress grades (so-called C and D grades) specify design stresses for bending, compression, tension and shear, as well as stiffness values and density (Institute 2016a).

LSL is a type of composite structural material that is composed of wood flakes that have been orientated in a specific direction. These wood flakes are then bonded together using adhesive and subjected to compression, resulting in the formation of panels that can reach a thickness of up to 90 mm (equivalent to 3.54331 inches). This material presents a compelling substitute for solid sawn lumber due to its superior qualities compared to solid lumber of the identical species, as well as its reduced variability. The production of LSL can be derived from trees with smaller diameters and lower quality, therefore mitigating our reliance on old age forests. The attainment of desired final qualities in LSL can be achieved through the meticulous management of many variables associated with the stranded lumber, resins, and pressing cycle. The qualities and performance of LSL are heavily influenced by the species of wood used in its production. The material characteristics of LSL are influenced by various factors, including the density of the panel, the species of strands used, and the orientation of the wood strands. Hardwoods, such as oak and beech, can be better suited for applications that demand more strength and durability than softwoods, such as pine and spruce, because they have higher densities and stiffness (Espinoza and Buehlmann 2018). In this regard, (Espinoza and Buehlmann (2018) reported that the CLT products made of hardwoods, namely beech and ash, are 275% stronger than the CLTs made from softwoods. Processing and manufacturing procedures used to make LSL can also significantly affect its characteristics. Moreover, the glueability of the wood and the accuracy of the chipping/slicing process are two critical aspects in the manufacturing of LSL. The glueability of wood refers to its ability to adhere with adhesives successfully, whereas the chipping/slicing procedure includes cutting wood logs into thin, elongated strands. The geometry of these strands is an important factor in determining the mechanical characteristics of LSL, such as strength and stiffness. As a result, generating high-quality LSL requires strong adhesive bonding and accurate strand geometry.

2.1 Different hardwoods

This literature study intends to guide future advancements in LSL material by reviewing the feasibility of employing four distinct wood species—Turkey oak (*Quercus cerris*), European hornbeam (*Carpinus betulus*), European beech (*Fagus sylvatica*), and domestic poplars (incl. *Populus alba*, *Populus nigra* and *Populus tremula*)—in LSL manufacturing. Hardwood species with suitable mechanical qualities, including different hardwoods, could have potential for LSL manufacture. As a dense and sturdy hardwood with a high modulus of elasticity and modulus of rupture, Turkey oak is a promising material for LSL manufacturing. Another heavy and sturdy timber, hornbeam offers great promise for usage in LSL because of its high compressive strength. There have been promising findings regarding the dimensional stability and mechanical qualities of LSL made from the stiff and strong poplar wood (Moradpour et al. 2018). The features and various characteristics of Hungarian hardwood species are shown in Tables 1 and 2. In terms of sustainability and cost-effectiveness, poplar, a fast-growing and commonly accessible species, has been discovered to have acceptable mechanical qualities for use in LSL manufacture (Van Acker et al. 2016).

These hardwoods all have different qualities that might make them ideal for certain LSL uses. In contrast to hornbeam, which may be better suited for usage in locations with low humidity or moisture exposure, Hungarian Turkey oak may be ideal for use in heavy-load applications. Technically, the density of different wood species has a crucial role in the production of LSL. LSL production is limited to hardwoods with low and medium density. The possibility

Table 1 Different features and characteristics of Hungarian hardwoods (Hasan et al. 2021a; Molnár 2016; Monlar Sandor 2002)

Hardwoods properties	Beech	Hornbeam	Turkey oak	Poplars
Names	Hungarian: bükk Scientific name: *Fagus sylvatica* English: Beech, German: Buche, French: hetre	Hungarian: gyertyán Scientific name: *Carpinus betulus* English: hornbeam, ironwood, German: Hainbuche, Weißbuche French name: Charme	Hungarian: csertölgy Scientific name: *Quercus cerris* English: Turkey oak, German: Zerreiche, French: chene chevelu	Hungarian: fehérnyár, rezgőnyár, feketenyár Scientific name: *Populus spp.* English: White poplar, Aspen, Black poplar
Morphological characteristics	Trunk shape is 35 to 40 m in height, bole length: 15 to 20 m. Breast height diameter: 0.4 to 0.7 m Branches are thinner Bark is 1 to 2 cm thin and ash-grey in color	20 to 25 m height, breast height diameter: 50 to 60 cm Branches are thinner Bark is 1 to 2 cm and dark grey in color Life span is 120 to 150 years but needed 60 to 80 years for harvesting	25 to 30 m height, trunk length: 12 to 15 m. Diameter: 0.3 to 0.5 m Straight and cylindrical trunks. Coarser bark, greyish bark, Bark is 1 to 10 cm	White poplar: 20 to 30 m height, trunk length: 12 to 15 m. Diameter: 0.5 to 1.0 m Smooth bark, greyish
Defects and limitations	Red heart disease, red beech infection by fungimoustach-like lines, suffocation caused by fungi	Prone to attack by some fungi like *Trametes, Serpula*	Three basic defects: red heart, frost ribs, and ring shakes	Knots, frost cracks, red heart, prone to biotic attack
Durability	Varies depending on various condition: 2–5 years: soil contact, 10 to 40 years: outdoor condition, 30–120 years: under water, 200–700 years: permanent dry condition	Varies depending on various condition: 35 years: outdoor condition, ~500 years: under water, ~800 years: indoors		Varies depending on various condition: 2–5 years: soil contact, 5 to 30 years: outdoor condition, 5–50 years: under water, 50–400 years: permanent dry condition

Table 2 Different physical, mechanical, and chemical properties of different hardwoods (Hasan et al. 2021a; Molnár 2016; Monlar Sandor 2002)

Hardwoods properties	Beech	Hornbeam	Turkey oak	Poplars
Physical properties				
Density (oven dry)	490 to 880 kg/m^3	500 to 820 kg/m^3	570 to 850 kg/m^3	White p.: 450 kg/m^3, Aspen: 490 kg/m^3, Black p.: 450 kg/m^3,
Porosity	55%	48%		
Shrinkage				
Tangential	11.8%	11.5%	8.5 to 9.8%	5.9 to 8.6%
Radial	5.8%	5.2 to 6.8%	4.4 to 4.9%	3.1 to 5.3%
Longitudinal	0.3%	0.5%	0.3 to 0.4%	0.2 to 0.4%
Volumetric	14.0 to 21.0%	18.8%	12.9 to 14.6%	9.5 to 14.7%
Mechanical properties				(white poplar)
Tensile strength	57 to 180 MPa	47 to 200 MPa,	100 to 139 MPa	82.3 MPa
Bending strength	74 to 210 MPa	58 to 200 MPa	94 to 136 MPa	67.5 MPa
Comp. strength	41 to 99 MPa	54 to 99 MPa	44 to 71.3 MPa	38.3 MPa
Impact strength	3 to 19 J/cm^2	8 to 12 J/cm^2	10 J/cm^2	4 to 5 J/cm^2
Hardness (Brinell)	72 MPa (end grain) 34 MPa (side grain)	71 MPa (end grain) 29 to 36 MPa (side grain)	57 MPa (end grain)	27 MPa (end grain)
Chemical properties				
Cellulose	45.4%	43%	42–47%	45 to 52.4%
Hemicellulose		32 to 34.5%	20–27%	
Pentosans	17.8%,			17.8%,
Hexosans	4.4%			
Lignin	22.7%	19.3 to 22.5%	25 to 27%	23.2 to 25.2%
Ash	1.6%	0.5%	Others: 3–4%	0.41 to 0.89%
Extractives: (benzene-alcohol extraction)	0.7%	2.4%		2.3 to 3.2%
pH value	5.1 to 5.4	5.2	4.9	5.8

of using some hardwoods with an oven-dry density above 750 kg/m^3, such as oak, hornbeam, and beech, for the production of LSL poses challenges. The compressibility of wood also plays a crucial role in the manufacturing processes of LSL and Oriented Strand Board (OSB). More study is required to determine the best ways of processing and uses for LSL made from these hardwoods. All things considered, the building sector stands to benefit from the investigation of these hardwood species for LSL production thanks to the possibility of improved sustainability, lower costs, higher mechanical attributes and wider applicability.

2.1.1 Turkey oak

There is a lot of potential for the manufacture of LSL from Turkey oak (*Quercus cerris*) in Hungary. It is also known as csertölgy in Hungary, Zerreiche in German, and chehe chevelu in French (Monlar Sandor 2002). Turkey oak is native to South-Eastern Europe and the central European region as well. In Hungary, this particular species is the most prevalent, covering approximately 11.4% of the country's forestry area, which accounts for 176,000 hectares (Monlar Sandor 2002). It thrives in hilly and mountainous regions, where it is favorably grown. A typical Turkey oak tree is shown in Fig. 1 with its macroscopic and microscopic structure as well. However, Turkey oak is susceptible to diseases, particularly during its mature stage, typically around 60 to 80 years old. When affected by diseases, the growth of Turkey oak can slow down significantly. The density of Turkey oak ranges from 570 to 850 kg/m^3 in oven-dry state and 1000 to 1100 kg/m^3 in green state (Monlar Sandor 2002). The strength of the wood is truly remarkable, with impressive values across various parameters. Tensile strength ranges from 100 to 139 MPa, bending strength from 94 to 136 MPa, and compression strength from 44 to 71 MPa at 12% moisture content and in the air-dried condition (Table 1). This natural tree species has several qualities that make it an excellent choice for LSL construction. The wood from the Turkey oak tree is renowned for its strength and longevity as well as its exceptional mechanical characteristics (Ciesla 2002; Merela and Čufar 2013). Because of its high density, it is ideal for load-bearing applications in construction, especially for its increased

Fig. 1 Photographs and morphology of Turkey oak in Hungary: **A** Turkey oak tree, **B** Turkey oak wood microscopic image, and **C** Turkey oak woods. Digital photographs taken by Dr. Miklós Bak (SOE)

strength and dimensional stability. Turkey oak is widely available and easily harvested, making it a viable option for LSL manufacturing in Hungary. Different characteristics of Turkey oak are provided in Table 1. The expansive woods of Hungary, notably the Turkey oak forests, may be responsibly maintained to provide a reliable source of raw materials (Krstic et al. 2010; Vukin and Rakonjac 2013). The manufacturing of LSL from Turkey oak may contribute to the use of sustainable and renewable resources, decreasing reliance on imported or less ecologically friendly alternatives by taking advantage of this underutilized local resource.

The inherent qualities of Hungarian Turkey oak also contribute to the wood's superiority as an LSL material. Natural insect and fungal resistance in the wood reduces the need for chemical treatments and preservers (Seth 2003). LSL panels manufactured from Turkey oak are well-suited for usage in areas where moisture, humidity, and possible biological deterioration pose substantial issues due to the wood’s inherent resilience. By investigating the viability, benefits, and drawbacks of using Turkey oak in Hungary for LSL production, we can better assess the resource's potential.

2.1.2 Hornbeam

The hornbeam, or *Carpinus betulus* L., is a common European hardwood tree found across Hungary (Fodor et al. 2018; Fodor), which is called gyertyán locally (Fig. 2). It is predominantly cultivated and found in the mountainous regions of Hungary, typically up to an altitude of 600 to 700 m. It occupies approximately 6.2% of the country's forested area, which amounts to approximately 95,400 hectares. The annual production of hornbeam in Hungary ranges between 400,000 and 500,000 m^3 (Monlar Sandor 2002). Interestingly, it is a very fast growing plant and can tolerate extreme weather too. It has a number of desirable qualities that make it a potential material for LSL manufacturing. In outdoor applications, it remains durable for long time, even as long as 35 years if there is no soil contact (Monlar Sandor 2002). However, decay will start within 2 to 3 years if contacted with soil. However, it can be more durable underwater and in an indoor environment, lasting for 500 and 800 years, respectively (Monlar Sandor 2002). There are a broad variety of building uses for hornbeam wood due to its high strength, density, and wear resistance. Hornbeam has a long history of use in Hungary’s furniture,

Fig. 2 Photographs and morphology of hornbeam in Hungary: **A** hornbeam tree, **B** hornbeam wood microscopic image, and **C** hornbeam woods. Digital photographs taken by Dr. Miklós Bak (SOE)

flooring, and joinery industries. It can withstand intense pressure and harsh circumstances because of its thick and sturdy composition. These characteristics are also useful in LSL manufacturing, where the resulting panels can have excellent strength.

The easy access to hornbeam in Hungary is another factor in the country's promising LSL production potential. Hornbeam woods, part of the country's considerable forest resources, provide a renewable and locally obtained material for the building sector. Researchers can maximise the performance and durability of the resulting LSL by figuring out the best processing methods and adhesive compositions, and they can do so by investigating the possibilities of hornbeam for LSL.

2.1.3 Beech

The beech tree (Fig. 3), or *Fagus sylvatica*, is a common deciduous tree species in Europe and Hungary (termed as bükk locally). There are approximately 13 species of beech found in the northern temperate areas, playing a significant role in Europe. This species is primarily distributed in the central European region, but it can also be found in parts of England and southern Scandinavia. Its growth occurs within latitudes ranging from 40° to 60° (Fodor 2023). In mountainous regions, it thrives at altitudes of 600–800 m (Fodor 2023). Beech is known for its low durability, with a lifespan of 2 to 5 years when in contact with soil, 10 to 40 years in outdoor environments, 30 to 120 years when submerged in water, and 200 to 700 years under dry conditions (Monlar Sandor 2002). Because of its excellent quality timber, it has great potential as a source for LSL production. Beech has been used for building, making furniture and laying floors in Hungary for a very long time. Beech wood has great strength, stiffness, and wear resistance, among other desirable mechanical attributes (Gao and Gong 2021). Because of these qualities, it is ideal for use in load-bearing building applications. When compared to solid sawn timber, Hungarian beech LSL provide benefits including better dimensional stability and an improved strength-to-weight ratio. Composite lumbers like LSL may be used for anything from beams and columns to decorative accents and even furniture (Van Acker 2021a, b).

Also, in Hungary, beech is a renewable and easily accessible material. The country's massive, sustainably maintained beech forests provide a reliable source of raw materials. Using beech for LSL production is an example

Fig. 3 Photographs and morphology of beech in Hungary: **A** beech tree, **B** beech wood microscopic image, and **C** beech woods. Digital photographs taken by Dr. Miklós Bak (SOE)

of supporting sustainable forestry practises and making better use of locally available resources.

2.1.4 Domestic poplar (*Populus* spp.)

Poplar is a widely distributed tree genus found in Hungary, known for its fast growth and versatile wood properties. The *Populus* genus encompasses approximately 35 species, primarily belonging to the *Salicaceae* family. In Hungary, nearly 16 native species of *Populus* have been identified (Gao and Gong 2021). From an industrial perspective, two distinct groups of poplars are commonly used in Hungary: native poplars and hybrid poplars. Native poplars include white (Fig. 4) and grey varieties, while hybrid poplars are improved and selectively bred types (Gao and Gong 2021). The most common domestic poplars in Hungary are *Populus nigra* (black poplar), *Populus alba* (white poplar), and *Populus tremula* (aspen). The very common natural hybrid of *P. alba* and *P. tremula*, known as *Populus* × canescens (grey poplar) is also considered domestic poplar. Poplar holds significant importance within Hungary's forestry sector, covering approximately 1.5 million hectares of land (constituting 9.6% of the country's total forestry) (Gao and Gong 2021). Annually, these poplar plantations yield a production of 1.3 to 1.5 million cubic meters of wood (equivalent to 23 to 25% of the country's total harvest) (Gao and Gong 2021). Its suitability for engineered wood production has attracted considerable attention due to its abundance and renewable characteristics. In Hungary, domestic poplar plantations have been established to meet the growing demand for wood products, making it an economically and environmentally viable option for LSL production. The wood of domestic poplar is lightweight yet strong, making it an ideal candidate for LSL products (Balatinecz et al. 2014). It exhibits good dimensional stability and uniformity, which are essential for construction applications. Additionally, the fine texture and attractive appearance of domestic poplar wood make it suitable for a wide range of interior applications, such as furniture, cabinetry, and decorative elements (Ding et al. 2022; Laboratory 1987). Sometimes, poplar is also densified highly through modifying multi size pores internally through gas expansion which is also termed as impregnation technique. Therefore, Zhang et al. (2023) suggested an impregnation technique (Fig. 5) for dredging the internal liquid flow pathways of poplar (*Populus L.*) wood in order to obtain a high degree of densification. The modification of poplar wood brings about changes in both its crystallinity and chemical structures. These alterations were examined

Fig. 4 Photographs and morphology of poplar in Hungary: **A** beech tree, **B** beech wood microscopic image, and **C** beech woods. Digital photographs taken by Dr. Miklós Bak (SOE)

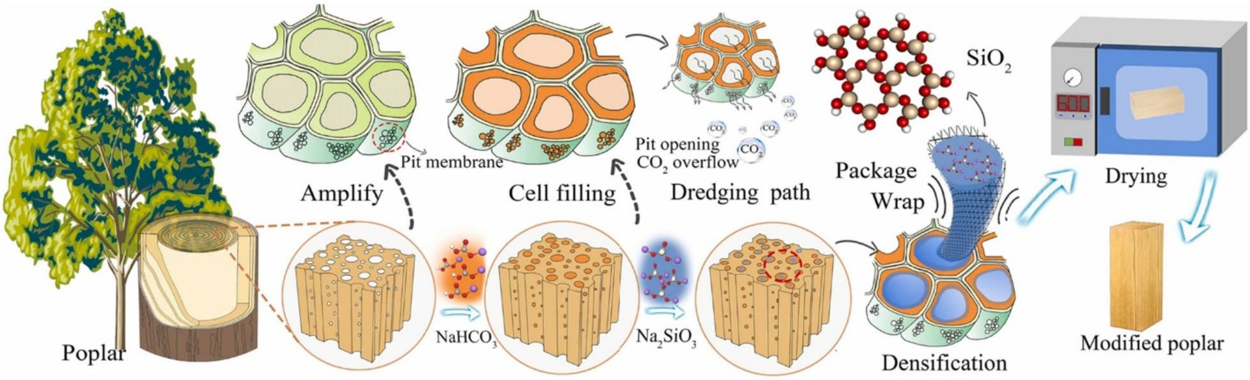

Fig. 5 Preparation method and reaction mechanism toward poplar wood densification process. Adapted with the permission from Elsevier (Zhang et al. 2023). Copyright, Elsevier, 2023

through FTIR, XPS, and XRD analyses, which revealed the wood's modified characteristics (Minnie 2023). Additionally, the modified poplar wood exhibits flame retardant properties (Minnie 2023).

The use of domestic poplar for LSL production offers several benefits. Firstly, it supports sustainable forestry practices as poplar trees can be harvested relatively quickly, typically within 10–15 years (Rockwood et al. 2004; Worrell 1995), making them an excellent renewable resource. Moreover, the establishment of poplar plantations contributes to carbon sequestration and ecosystem restoration, making it an environmentally friendly option for LSL production. Secondly, domestic poplar LSL products have excellent structural properties, including high bending and shear strength, which make them suitable for load-bearing applications in the construction industry (Sun et al. 2021). LSL is frequently produced utilizing wood strands derived from several species of poplar trees, such as balsam and aspens poplars (Canada, 2022).

3 LSL as an engineered wood product

Engineered wood products (EWPs) are composite materials manufactured from joined wood fibers, strands, veneers, or particles. These products are intended to overcome the constraints and unpredictability of genuine solid wood, while also providing improved structural performance and adaptability. The LSL, OSB, particleboard, fiber board, and other engineered wood products are some of the examples of EWPs. The building and construction sector increasingly uses LSL products, a form of EWP. Lumbers are often manufactured in large widths and thicknesses, making them well-suited for use as beams, columns, and framing (Vladimirova and Gong 2022). The LSL product is very reliable and uniform, exhibiting remarkable mechanical qualities including strength, stiffness, and dimensional stability. There is a wide range of qualities and uses for LSL products since they may be constructed from many different types of wood. There may be less waste and fewer repairs needed over time since LSL products are less likely to warp, split, or shrink. There is a lot to learn about the possible uses and qualities of LSL products, regardless of their benefits. To better understand the potential of various hardwood species for LSL production and to influence future development and optimisation of LSL materials, further study is needed.

4 Fabrication of LSL with specification

The wood strands in LSL are generally oriented in the longitudinal direction to enhance the structural integrity of the final product. According to European standard, the strands must not exceed a dimension of 2.54 mm, and their average length should be 150 times of the least dimension (minimum) ((EAD), 2018). In another study it was reported that, the LSL should be of 300 mm length and 0.8 to 1.3 mm thickness (Asdrubali et al. 2017). Typically, the moisture content remains 6–10% for the LSL products ((EAD), 2018). Researchers reported couple of studies for the fabrication of LSL products (Gong 2019; Mayo 2015). The fabrication of LSL needs to follow several steps as shown in Fig. 6. First, the wood strands are chopped and milled into uniformly sized pieces in preparation for LSL fabrication. Wood strands may be made in a variety of sizes to provide the desired effect and meet specific requirements.

The width of the strands used in the production of LSL is just as crucial as the strand size. The 300 mm to 3000 mm range for lumber width applies to a wide variety of uses and construction methods. Wider lumber is utilised for bigger parts like floor and roof systems, whereas narrower lumbers are used for smaller elements like joists and beams

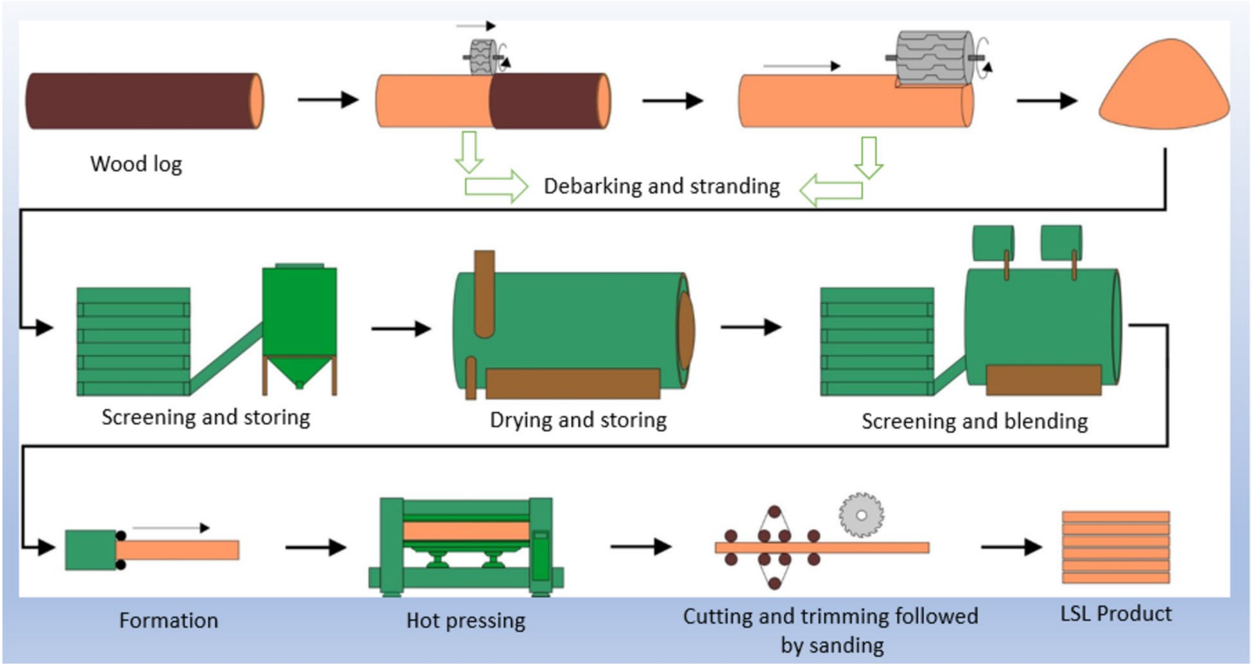

Fig. 6 LSL products formation. Drawn by: Dr. Peter Gyorgy Horvath, edited by Dr. K. M. Faridul Hasan

since they are simpler to build. The mechanical qualities and applicability of an LSL are also heavily dependent on its thickness. The typical width of a LSL is between 44 and 89 mm, and depth 24.1 to 40.6 cm (Minnie 2023).

LSL's final qualities are also heavily influenced by the resin binder used in the production process. The expected qualities and performance requirements of the final product will determine which resin will be utilised. Melamine–urea–formaldehyde resin, for instance, is utilised for its water resistance and fire retardant qualities, whereas phenol–formaldehyde resin is often employed for high-strength applications (Hasan et al. 2021a, b, c, d, e, f). In order to get the right qualities and performance for a given application, manufacturers of LSL must choose the right species of wood, strand dimensions, lumber width, and resin binder. LSL manufacture utilising Hungarian Turkey oak, hornbeam, beech and domestic poplar is a promising but understudied field that might pave the way to more environmentally friendly and economically viable building materials. The production process (Fig. 6) of LSL involves several key steps (Moradpour et al. 2018):

- Firstly, log conditioning is carried out to prepare the logs for further processing. This may include debarking and removing any defects or irregularities from the logs.
- The next step is the stranding process, where the logs are transformed into small strands. This is typically done by mechanically cutting or shredding the logs into thin, elongated pieces. These strands are then dried to reduce their moisture content, ensuring dimensional stability and preventing mold or decay during the subsequent stages.
- Once the strands are dried, they go through a blending process. In this step, the strands from different log batches or wood species are combined to achieve a desired blend and ensure consistent material properties throughout the LSL panel.
- The blended strands are then formed into a mat or layer, where they are oriented in a specific arrangement to optimize the mechanical properties of the final LSL product. This mat is then subjected to high pressure and temperature during the pressing stage. The application of heat and pressure activates the resin binder, which bonds the strands together and forms a solid, cohesive LSL.
- After pressing, the LSL shall undergo final processing, which may include trimming, sanding, and cutting to the desired dimensions and specifications.
- Overall, the LSL production process encompasses log conditioning, stranding, drying, blending, forming, pressing, and final processing stages, each playing a crucial role in transforming raw materials into high-quality LSL products suitable for various construction applications.

Sometimes the LSL could also be reinforced with other synthetic fibers like as glass fiber as well to tune their properties like MOR, MOE, compression, and impact strength. In this regard, a recent study has shown that the glass fiber reinforcement of LSL (made from poplar) with pMDI has significant potential ((EAD), 2018). This investigation also mentioned that when pMDI was used as the resin and GFRP (glass fiber reinforced polymer) was used as the reinforcement, the best results were seen: a 123% rise in MOR, 114% increase in MOE, and a 90% increase in compression strength compared to the control samples ((EAD), 2018). The fabrication mechanism of their product is shown in Figure 7.

5 Properties of LSL products

LSL products are engineered wood products compressed and bonded together with a synthetic resin binder. The end result is a uniformly high-quality material that is also robust and long-lasting. Wood species, production method, and resin

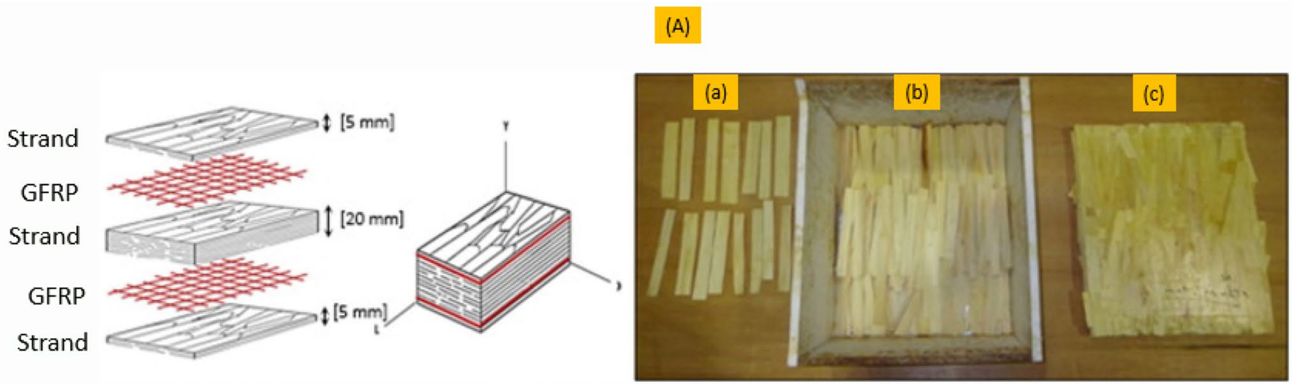

Fig. 7 Fabrication schematics for LSL products: laboratory and schematics of LSL production protocol. Copyright, Elsevier, 2018 (Moradpour et al. 2018). Adapted with the permission from Elsevier. GFRP: glass fiber reinforced polymer

binder all have a role in shaping LSL panels final characteristics. LSL products are perfect for usage as beams, columns, and joists because of their great strength and stiffness, which are some of its important qualities (Sun et al. 2021). In addition, LSL have great dimensional stability, meaning they don't warp, twist, or shrink excessively when subjected to variations in temperature or humidity (Rämäkkö, 2021). Hwang and Komatsu (2002) reported that developed LSL products showed standardized mechanical and physical properties (MOE by 0.95 (0.24 GPa) in longitudinal direction and moisture content by 13 (1.18%)). In another study (Aro et al. 2017), it was reported that increased temperature decreases the mechanical properties of LSL. The same study post treated the wood products at different temperatures, starting from 140 °C and found that MOE values were not much changed, however, the highest tension was noticed at 180 °C by 11.8 GPa (Aro et al. 2017). Additionally, they have further claimed that, the tensile strength (10.8 MPa) dropped by 70% at that temperature (180 °C) compared to that of the control (Aro et al. 2017). They are dependable in situations where dimensional stability is essential, such as in flooring and roofing systems, because of this quality.

Because of its high screw holding capability (Bayatkashkoli and Faegh 2014; Maleki et al. 2017), LSL is often used in framing and sheathing systems and other situations where a solid connection between the lumber and other materials is required. In addition to its durability and longevity, it is also resistant to rot and insect damage, making it an excellent building material. LSL developed from poplar hardwood also provides significant mechanical properties. As a result of its many useful characteristics, LSL is increasingly becoming a popular building material option.

5.1 Mechanical properties

LSL panels are well-liked in the building industry due to their excellent mechanical characteristics. A typical testing is shown in Fig. 8. Eventually, it all comes down to a matter of opinion, but it is safe to say that the product's mechanical characteristics play a major factor in the debate. It is reported that, LSL developed from poplar showed 104.67 MPa MOR and 13,517 MPa MOE values, whereas the internal bonding strength was 0.98 MPa, which is also meeting the standard requirement of the products (Bayatkashkoli and Faegh 2014). High stiffness and strength attributes have been observed in LSL panels crafted from various hardwoods (Table 3). The density of the LSL is affected by the density of the wood strands used and the quantity of resin binder used during production, and this in turn affects the lumbers stiffness and strength attributes. In general, the stiffness and strength capabilities of LSL are best when they are crafted from higher density wood species and have a higher resin content.

Mechanically, LSL products are valued for their stiffness, strength, and dimensional stability. Some of the hardwood-based engineered wood products mechanical and physical properties are shown in Table 3. The term "dimensional stability" is used to describe the product's capacity to retain its

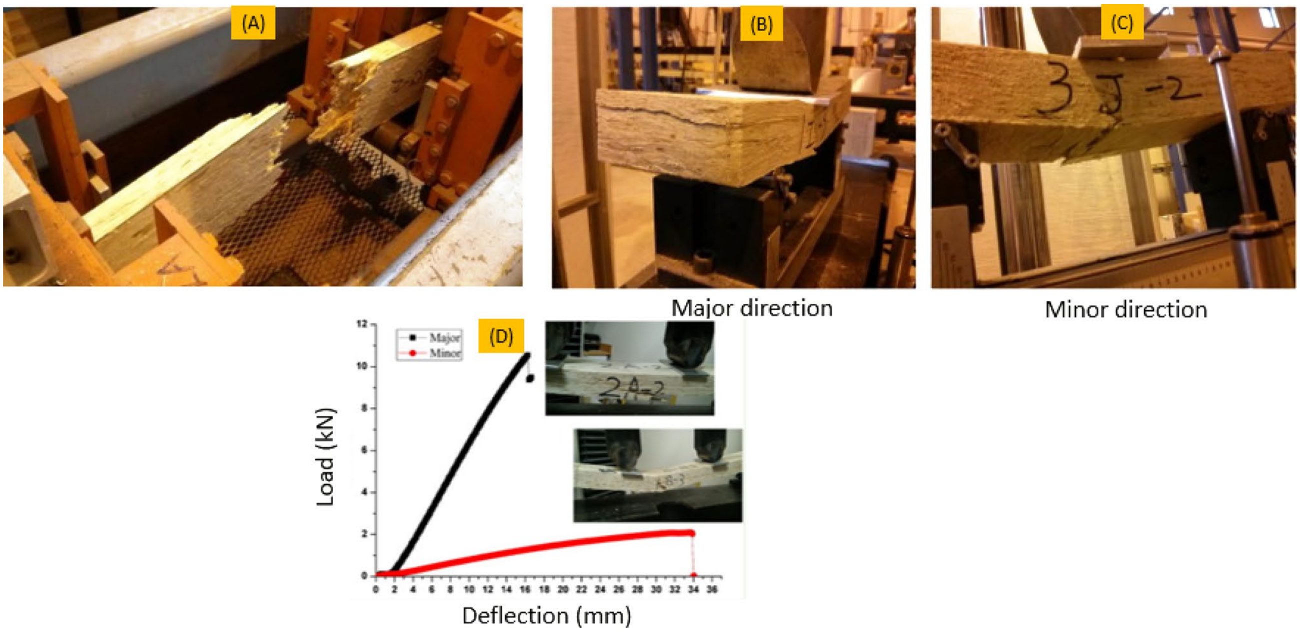

Fig. 8 Different tests of LSL: **A** typical failure of LSL under tension, typical failure of LSL under bending, major (**B**) and minor (**C**) direction, and the load–deflection curves (**D**). Adapted with the permission from Elsevier (Wang et al. 2015). Copyright, Elsevier 2015

Table 3 Mechanical properties of some engineered wood products like LSL

Wood species	Tensile Properties	Flexural Properties	Physical Properties	References
Aspen (*Populus tremuloides*)	Tensile strength: 45.11 MPa	MOR: 48.19 MPa MOE:11.609 GPa		Wang et al. (2015)
Aspen (*Populus tremuloides*) (control sample)		Density: 657 (42.61) kg/m^3 MOR: 11.858 MPa MOE: 47.48 GPa	MC: 8.9 (0.6) % Swelling: 1.05 to 1.2%	Denizli (1997)
Paulownia (control)	Shear strength: 10.34 MPa IBS: 0.84 MPa	Density: 88.85 kg/m^3 MOR: 88.85 MPa MOE: 10.763 GPa		Bayatkashkoli and Faegh (2014)
Mixed hardwood	Maximum tensile strength: 35.8 (5.47) MPa	MOE:11.1 (1.19) GPa	MC: 6.8%	Aro et al. (2017)

*MC: Moisture content, MOE: Modulus of elasticity, MOR: Modulus of rupture

original dimensions in the face of changes in its surrounding environment, such as temperature and humidity (Hasan et al. 2021d; Hasan et al. 2021b). For uses where dimensional stability is paramount, such as flooring and decking, research shows that LSL crafted from Hungarian hardwoods perform well. Hungarian LSL products developed from the hardwoods offer promising mechanical qualities for a range of building uses (Horváth et al. 2012; Molnar 2008). Although the potential of these wood species for LSL manufacture is promising, additional study is required to optimise the manufacturing process.

5.2 Chemical properties

Generally, wood species contain identical proportions of cellulose, hemicellulose, and lignin. The presence of extractives and resins in wood, on the other hand, might affect the bonding qualities. LSL is a composite material composed of small strands of wood and a synthetic resin binder. The LSL product's performance, durability, and applicability are all dependent on the chemical characteristics of the constituents like wood strands and resin (Smith and Wu 2005; Vnučec et al. 2017). The resin binder utilized during its manufacturing process significantly influences the chemical properties of LSL, which in turn influences its adhesion, bonding properties, water resistance, and fire retardancy. Resin binders like phenol–formaldehyde (PF) and melamine-urea–formaldehyde (MUF) are commonly employed in LSL production. Moreover, the choice of resin type also affects the properties of other wood products, such as PSL. Consequently, Moradpour et al. (2019) conducted an investigation to explore the effects of varying lumber thickness and different resin types. Their findings revealed that both the physical and mechanical properties exhibited variations based on the thickness of product and type of resin used (Moradpour et al. 2019). The study also noted that due to the exceptionally high modulus of rupture (MOR) value obtained, the chances of deformation are significantly reduced, making the material suitable for beam applications (Moradpour et al. 2019). Several variables affect LSL's chemical qualities, including the resin binder used, the wood strand density and size, the pressing duration and temperature, and the conditioning and drying procedures. As key factor in indoor air quality and human health, formaldehyde emission levels may be used to characterise the chemical features of LSL (Vnučec et al. 2017). Moreover, volatile organic compounds (VOC) emitting from the building materials like structural beams or furniture are another challenge for indoor air quality. To further improve its functionality and lifespan, LSL may be chemically treated with a wide range of convenient chemicals.

This study focuses on exploring the chemical characteristics of LSL derived from different hardwoods found extensively in the European region. Due to their unique densities and chemical compositions like cellulose, hemicellulose, lignin, and so on (Fig. 9), the performance and durability of LSL manufactured from these wood species may vary. The different bonds are created like the hydrogen, ether, and ester bonds between the polymers of woods and the adhesives (Ye et al. 2022).

5.3 Physical properties

LSL products have several physical properties that make them an attractive option for construction applications. LSL products' consistent dimensions are a major advantage. Because of how they are made, LSL products have limited expansion when the weather changes because of their low equilibrium moisture content and uniform density (Sandberg et al. 2023). LSL is ideal for framing and other load-bearing applications because of its dimensional stability, which also contributes to its high nail and screw holding capability (Alinoori et al. 2020; Sandberg et al. 2023). LSLs are strong and stable in their dimensions, and they also insulate well against sound and heat. LSL may increase the energy efficiency and comfort of buildings because of their uniform density and low moisture content, which prevents sound transmission

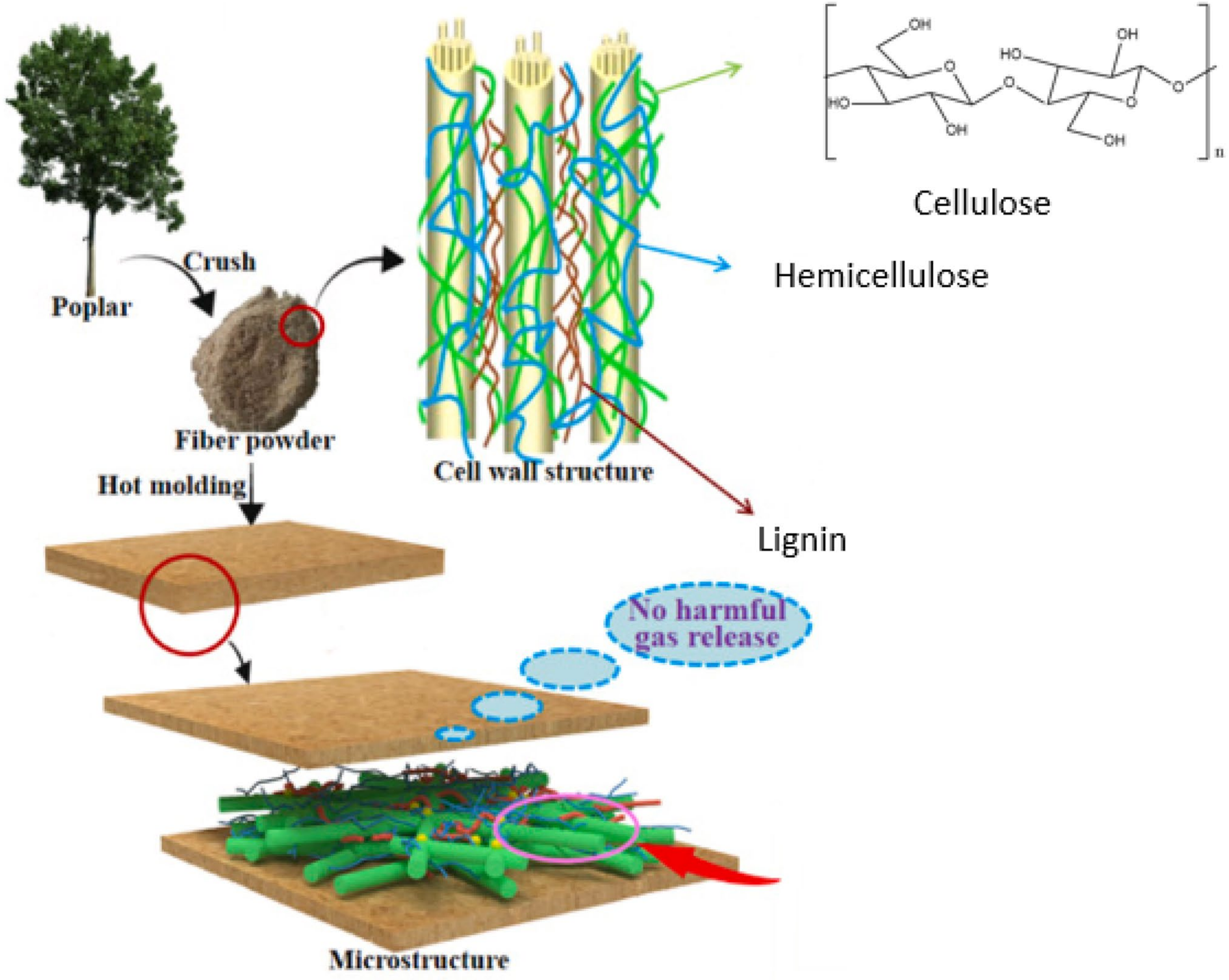

Fig. 9 Physico-chemical reaction mechanism of cellulosic materials and adhesives. Copyright, Elsevier, 2022 and Springer Nature, 2021 (Mahmud et al. 2021; Ye et al. 2022). Adapted with permission from Elsevier and Springer Nature

and reduces heat loss. In general, LSL is a promising material for a variety of building applications due to its advantageous physical qualities. Existing results are encouraging; nevertheless, further investigation is needed to establish the potential of underutilized hardwood species for LSL production.

When exposed to wet conditions, LSL thickness stability is a crucial factor to take into account. LSL's dimensional stability is susceptible to variations in moisture content, much like other engineered wood products. The wood fibers in LSL can absorb water when exposed to high humidity or direct moisture exposure. The fibers may expand as a result of this moisture absorption, increasing the LSL panel's total thickness. On the other hand, when the moisture content drops, such as in dry settings, the wood fibers may lose moisture and shrink, resulting in a decrease in the LSL panel's thickness. The functionality and structural reliability of LSL may be affected by these dimensional changes. The possible thickness fluctuations might present problems in situations where accurate measurements are essential, such as manufacturing or building operations. For instance, LSL panels may expand or contract during installation if they are not adequately acclimated or shielded from moisture, which might result in fit, alignment, or even buckling problems. Different tactics can be used to alleviate concerns about thickness stability. These consist of:

A) Proper acclimation: Prior to installation, LSL panels should be given time to adjust to the respective ambient factors. This reduces the possibility of unforeseen dimensional changes based on moisture fluctuations.
B) Moisture barriers: Using moisture barriers, such as coatings or vapor retarders, can protect LSL from direct

water exposure while limiting dimensional changes and moisture absorption.

C) Sealing and finishing: By applying the proper sealants or finishes to the LSL surfaces, manufacturers may lessen the amount of moisture that is exchanged with the environment, reducing the risk of dimensional changes.

D) Design points of view: There are some situations where design adjustments, such as adding expansion joints or allowing for some tolerance in the dimensions, can assist to account for probable thickness variations in LSL caused by moisture effects.

When employing LSL, it is essential to thoroughly assess the moisture conditions and take into account the unique application needs. The longevity of LSL may be ensured by using the right installation methods, moisture management strategies, and environmental controls. Variations in moisture content can have an impact on the thickness stability of LSL. For LSL to be successfully used in a variety of applications, it is crucial to recognize and handle any potential dimensional deviations brought on by moisture effects. The possible thickness stability issues of LSL can be successfully handled by employing suitable measures, such as acclimation, moisture barriers, sealing, and design considerations.

5.4 Thermal properties

LSL’s thermal qualities are just as crucial to its usefulness in building as its mechanical ones. The insulation properties and fire safety of LSL panels are influenced by their thermal conductivity and heat capacity. According to recent studies, LSL's thermal qualities may change based on the kind of wood used, as well as the panel's orientation and strand density (Jerves et al. 2023). Higher density and more orientated strands in LSL panels have also been linked to improved heat conductivity, suggesting they may be better suited for usage in situations that call for greater structural performance (Sandberg et al. 2023; Sun et al. 2020). Tripathi and Rice (2017) investigated the thermal conductivity of engineered wood panels made from LSL and spruce wood. Surprisingly, the LSL-based products exhibited a higher thermal conductivity value compared to the spruce wood panels. Notably, both types of panels demonstrated thermal conductivity values ranging from 0.081 to 0.126 W/(m·K). It is important to note that the LSL product's precise composition, density, used resin, and manufacturing technique may all affect the thermal conductivity values. However, the inclusion of resin in LSL may also result in a variable density and structure, which might further change the thermal conductivity characteristics. It is significant to note that, with regard to thermal conductivity in LSL, thermal conductivity is generally higher in the direction parallel to the grain or the direction of panel thickness. This indicates that heat conduction is easier along the LSL panel's thickness than it is perpendicular to the panel.

Overall, it is necessary to have a firm grasp on the thermal characteristics of LSL panels constructed from various wood species and polymeric resin before considering their usage in buildings. In this regard, Bartlett et al. (2019b) investigated the pyrolysis, ignition, and combustion behavior pattern of woods and made an investigation where they found the heat flux 12 ± 2 kW/m^2 for pyrolysis and 17.5 ± 2.5 kW/m^2 heat of combustion (Bartlett et al. 2019a). Developing LSL panels with optimised thermal qualities for particular applications and enhancing their fire resistance features are two areas where future research has to be directed to enable their safe and sustainable usage in the building construction industry.

5.5 Durability

LSL is just as important as any other building material in terms of its durability. The strength and stability of LSL are two of the most significant elements in determining how long it will last. However, LSL's longevity is also influenced by things like the kind of wood used, the glue used to join the strands, and the surrounding climate. Hungarian hardwoods are just few of the wood species that have had their durability studied in this report. Depending on the use and climate, LSL crafted from various wood species has been demonstrated to have good to outstanding durability in these investigations. The glue that is utilised to bind the strands together in LSL is also very important to its longevity. PF and MUF (Hasan et al. 2021a, b, c, d, e, f) are the two most frequently utilised adhesives in engineered wood products manufacture, composites and with different other lignocellulosic products (Kim et al. 2018; Lin and Lee 2018). Concerns over PF's possible toxicity, however, have prompted the creation of less harmful adhesives such as soy-based alternatives. Overall, the longevity of LSL is a multifaceted problem that is affected by variables such as the kind of wood used, the glue used, and the surroundings (Abed et al. 2022; Porteous and Kermani 2013). To enhance better understanding of the potential of Hungarian hardwoods for LSL production and facilitate future development, it is crucial to conduct further studies specifically focusing on these wood species.

5.6 Fire resistance

The assessment of LSL performance in environments prone to fire or applications with fire safety concerns necessitates careful evaluation of its fire resistance. LSL, like other engineered wood products, has intrinsic features of fire resistance. However, the precise fire performance of LSL is contingent upon a multitude of conditions.

- The flame spread rating pertains to the velocity at which flames propagate across the exterior of a substance. LSL generally exhibits a low flame spread rating, which implies a comparatively less inclination to facilitate the propagation of flames.
- The charring rate refers to the phenomenon observed when wood is subjected to fire, resulting in the formation of a protective layer of charred wood. The fire resistance of LSL is enhanced by its characteristic of displaying a consistent and uniform rate of charring.
- The maintenance of structural integrity during a fire is seen as a notable benefit of LSL. Although LSL may undergo charring, it generally maintains a substantial proportion of its load-bearing capability, hence offering ongoing structural support even when subjected to fire.
- Fire retardant treatments have the potential to augment the fire resistance of LSL. These treatments have the potential to mitigate the flammability of wood and impede the pace of fire propagation, hence offering supplementary fire safety measures.

The fire resistance of LSL panels is another crucial aspect to think about. The char layer that forms on the surface of LSL panels manufactured from poplar and beech shields the inner core from fire, and so these panels have high fire resistance capabilities, according to studies (Bartlett et al. 2019a; Sandberg et al. 2023). The fire resistance qualities of LSL manufactured from other wood species are not yet well understood, and suitable fire-resistant coatings and treatments specifically for LSL panels are not yet available, although presumably the same fire retardants used for solid wood apply.

It is essential to acknowledge that the fire resistance of LSL can be subject to several influences, including the thickness of LSL panels, the kind and grade of glue used, and the presence of additional materials or finishes that may impact its fire performance. In the context of fire-resistant design and construction, adherence to pertinent building rules, standards, and regulations is crucial when employing LSL.

5.7 Sustainability

LSL is well-known for its sustainability in addition to its strength, durability, and low cost. Small strands of wood, often taken from fast-growing tree species like poplar and pine, are used to create LSL, which is one of its main benefits. Because of this, LSL has a smaller ecological footprint than alternatives like concrete and steel, which need extensive energy and material inputs during their manufacturing (Abed et al. 2022). As an added advantage, the LSL manufacturing process is a closed-loop system designed to reduce waste and maximise efficiency. The environmental effect of LSL manufacture is further mitigated by the use of a resin binder to compress the wood strands together; this binder is generally a formaldehyde-free and low-VOC glue. LSL has other environmental advantages during construction, in addition to its eco-friendly manufacturing process. LSL products are a viable alternative to solid sawn timber, which is often cut from valuable large diameter trees. Using LSL allows building projects to employ sustainably managed forests and lessen their dependency on old-growth forests. Not only LSL but different other engineered wood products also show sustainability features. Therefore, different models are reported to support this approach. A sustainable bioeconomy model was reported by Zeug et al. (2022) for the sustainable development goal for the LVL wood products in Germany (Fig. 10). Overall, LSL provides a greener substitute for conventional building supplies and may help make the construction sector more eco-friendly (Klarić and Obučina 2020). This study intends to contribute to the development and optimisation of LSL materials that are robust and sustainable by investigating the possibilities of LSL made of Hungarian and European hardwoods.

6 Application potential of LSL

Because of its exceptional strength and durability, engineered wood products like LSL products may be used for a variety of purposes in the building sector. LSL products are widely used for structural and non-structural uses alike, including framing, roof decking, flooring, and internal and external wall sheathing (Olorunnisola and Olorunnisola 2018). LSL is ideal for usage in tall structures because of its high strength and stiffness; it may offer the required support while decreasing the building's weight and expense. LSL products may be cut to almost any size or form, which is another one of its many benefits. Large LSL products may be produced, and they can also be trimmed to particular sizes for different uses (Feraboli 2008). That is why they work so well for modular and prefabricated building, when time and cost savings are paramount. Some typical applications of LSL are beams and headers, rails, door coor, stiles, wall coverings, trim board, and high wall studs, framing for windows (Canada, 2022). In comparison to materials like steel and concrete, LSL products have a low environmental impact. Buildings' carbon footprints may be lessened and sustainable development aided by LSL manufacture using wood species including Hungarian hardwoods like Turkey oak, hornbeam, beech, and domestic poplar that are harvested in a responsible manner (Kumar and Leggate 2022; Romagnoli et al. 2019). When it comes to a wide range of building uses, LSL products are a high-value, low-cost option. In this context, the term "potential" refers to the likelihood of a future event occurring.

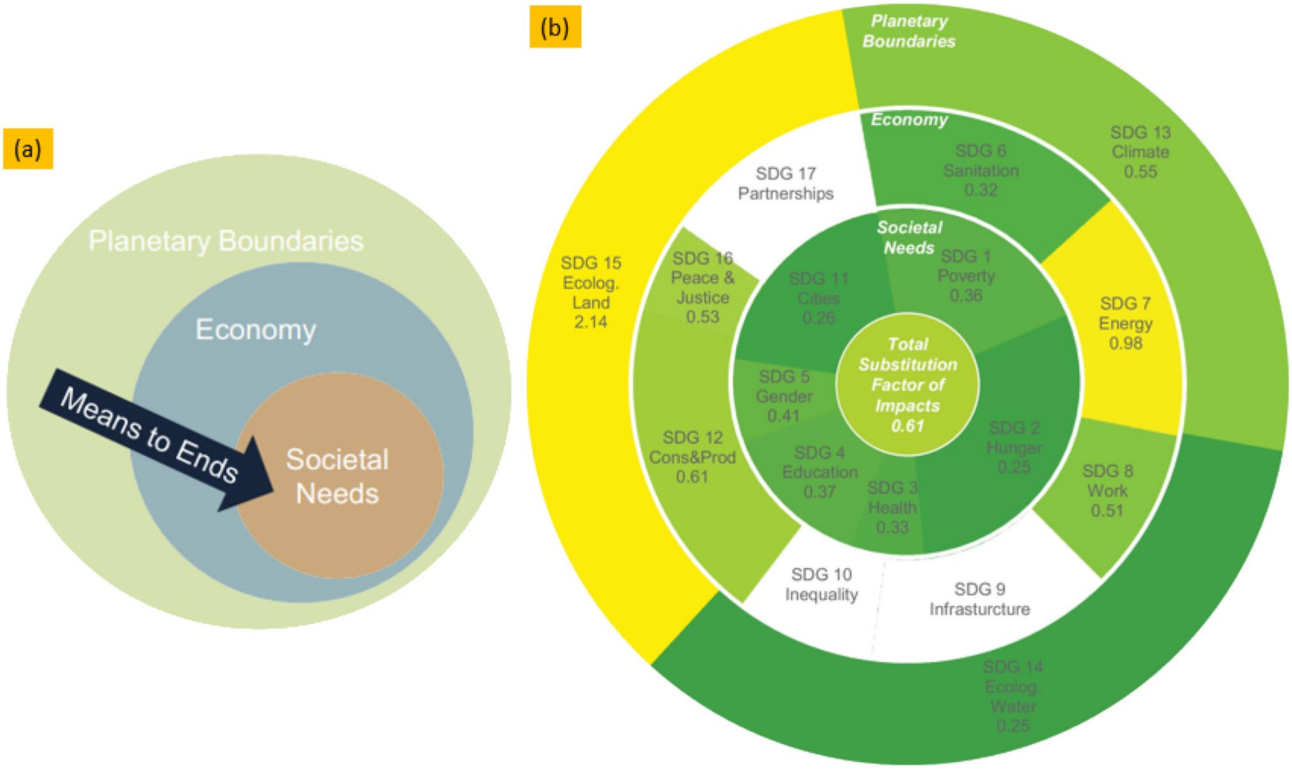

Fig. 10 **a** A Holistic Model of Sustainability and **b** A comprehensive sustainability framework utilized to compare the manufacturing processes of LVL and steel beams from a sustainability perspective. The study reveals that the importance of the SDGs (Sustainable Development Goals) for German Bioeconomy (BE) evaluations is directly proportional to their magnitude (Zeug et al. 2022). Copyright, Springer 2022. Adapted and republished under http://creativecommons.org/licenses/by/4.0/license/agreement

7 Economical aspects

Hardwoods play a significant role in European forestry, encompassing a substantial portion of the continent's wood stock. Broadleaved trees, specifically, contribute a substantial 15.0 billion m^3, accounting for approximately 43% of the total wood volume in Europe (van Acker 2021). However, while softwoods have traditionally been widely used for construction products in Europe, there is a growing interest in hardwoods as well. Hardwoods are increasingly gaining attention for their unique properties and potential applications. Hardwoods are increasingly utilized in the production of various engineered wood products, including construction materials, flooring, furniture, and building components, among others. LSL, a significant wood product, is increasingly preferred not only for its strength and durability but also for its cost-effectiveness compared to conventional timber. The short strands of wood used in LSL manufacture come from trees or logs that would not have been suitable for more conventional timber products. As a result, LSL may be made more cheaply by utilizing lower-quality wood that would have been thrown away (de Carvalho Araújo et al. 2019). In addition, LSL offers excellent dimensional stability and uniformity, which reduces scrap and boosts productivity on building sites (Mumma 1995). Consistency in material qualities and dimensions is particularly vital in large-scale building projects to ensure that design standards are met. The construction and building sector are responsible for consuming more than 35% of global energy and generating approximately 40% of carbon emissions. On the other hand, although concrete information regarding LSL production is limited especially in Europe, the production of LSL in North America was 316,465 m^3 in 2013, with a subsequent increase of 6% in 2019 to reach 333,780 m^3 (Khatri et al. 2021).

Understanding the environmental impacts of LSL through a cradle-to-grave Life Cycle Assessment analysis becomes crucial in this context. LSL production involves various resources, including wood, resin, electricity, gas, and other production inputs. The cradle-to-gate LCA analysis reveals that LSL production results in approximately 275 kg CO$_2$ equivalent of global warming potential and 598 MJ of fossil fuel depletion for 1 m^3 of LSL production (Khatri et al. 2021). Additionally, the production of resin contributes a significant amount of CO$_2$ emissions, accounting for approximately 124 kg CO$_2$ equivalent, representing nearly 45% of the total emissions (Khatri et al. 2021). Because it can be fabricated from rapidly renewable woods like Hungarian hardwoods, LSL is also an eco-friendly building material alternative.

It also needs to be noted that the affordability of LSL varies across Europe and other places like North America due to regional differences in pricing. LSL is becoming more well-liked in Europe as a practical substitute for conventional timber goods. In some European markets, its relatively lower cost compared to solid sawn timber or other engineered wood products may be attributed to the manufacturing techniques and the availability of raw materials. It is crucial to keep in mind, nevertheless, that cost elements might change based on a number of factors, such as regional market dynamics, supply and demand, transportation expenses, and local production capabilities. These elements may affect cost-competitiveness of LSL across many continents, including North American region.

8 SWOT analysis

SWOT analysis is another technique generally used in strategic planning for analysing the potential and the challenges of any products in the market (Hasan et al. 2021b; Hasan et al. 2022). It is a model for evaluating what elements, both internal and external, might strengthen or fail a project. Generally, there are few reports of SWOT analyses available for hardwood materials in the literature. However, some researchers still tried to create SWOT analyses on different wood-based products (Auer and Rauch 2021; Van Acker et al. 2016). Therefore, SWOT analysis has been carried out for these hardwood-based LSL products. Few points of the LSL panel from a SWOT perspective are provided below:

Strengths:

- Because of its durability and consistency, LSL may be used in many building contexts.
- Since LSL may be crafted from many different kinds of wood, it can be engineered for various applications.
- In comparison to solid timber, LSL is more affordable.
- Because of its high tensile strength and dimensional stability, LSL may be used in a variety of structural contexts.

Weaknesses:

- The appearance of LSL may be viewed unfavourable by some, and restrict its usage in places where solid wood timber would be preferred.
- If terms of flame resistance, LSL has the same issues as solid wood and other wood based products.
- Because of its increased density, LSL may be more challenging to process and transport than solid timber lumber.

Opportunities:

- Because it makes use of widely accessible wood species, LSL may help promote responsible forest management.
- Improved mechanical qualities and a wider array of potential uses may result from further investigation into and development of LSL processing techniques.
- The rising need for eco-friendly building supplies presents an opportunity for LSL.
- Recent raw material shortages and supply chain issues created an increased need for construction materials and more openness to innovative solutions.

Threats:

- In certain areas, the number of tree species suited for LSL production may be low.
- The demand for LSL may fall if more viable substitutes are developed.
- In certain cases, the usage of LSL might be hindered by revisions to legislation or building requirements.

In summary, the SWOT analysis highlights the importance of addressing the weaknesses of hardwood-based LSL products to achieve better outcomes. This can be accomplished by implementing innovative features such as enhancing appearance, improving flame resistance, and advancing processing techniques. Additionally, there are challenges to consider, along with potential substitutes for LSL products. These substitutes include engineered lumber, composite materials, and alternative building materials like steel or concrete. However, it is worth noting that LSL, being derived from sustainable and renewable hardwoods, holds significant potential.

9 Conclusion

LSL provides several benefits over regular hardwoods like Hungarian Turkey oak, hornbeam, beech, and even domestic poplars. LSL is a great option for many construction uses because of its reliability, longevity, and performance consistency. The mechanical, physical, thermal, and morphological qualities of LSL made from various hardwood species were found to be promising, suggesting that LSL has the potential to suit the demands of many different industries, including the building, furniture, and packaging sectors. The manufacturing of LSL from domestically available hardwood species may also help with sustainable forest management methods and lessen the need for imported wood. To completely comprehend the qualities of LSL made from these wood species and to improve the manufacturing method, however, further study is required. A possibility for economic and environmental advantages may be realized via the use of locally obtained wood species, which is highlighted in this analysis as the potential of LSL as a sustainable and adaptable resource for the wood sector.

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Data availability Data will be available on request.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest for the submitted work.

References

Abed J, Rayburg S, Rodwell J, Neave M (2022) A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. Sustainability 14(9):5570

Alinoori F, Moshiri F, Sharafi P, Samali B (2020) Reinforcement methods for compression perpendicular to grain in top/bottom plates of light timber frames. Constr Build Mater 231:116377

Aro MD, Wang X, McDonald DE, Begel M (2017) Tensile strength of thermally modified laminated strand lumber and laminated veneer lumber. Wood Mat Sci Eng 12(4):228–235

Asdrubali F, Ferracuti B, Lombardi L, Guattari C, Evangelisti L, Grazieschi G (2017) A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications. Build Environ 114:307–332

Auer V, Rauch P (2021) Developing and evaluating strategies to increase the material utilisation rate of hardwoods: a hybrid policy Delphi-SWOT analysis. Eur J Wood Prod 79(6):1419–1433

Balatinecz J, Mertens P, Boever LD, Yukun H, Jin JuWan JJ, Acker JV (2014) Properties, processing and utilization. Poplars and willows: trees for society and the environment. CABI Wallingford, London, pp 527–561

Bartlett AI, Hadden RM, Bisby LA (2019a) A review of factors affecting the burning behaviour of wood for application to tall timber construction. Fire Technol 55:1–49

Bartlett AI, Hadden RM, Bisby LA (2019b) A review of factors affecting the burning behaviour of wood for application to tall timber construction. Fire Technol 55(1):1–49. https://doi.org/10.1007/s10694-018-0787-y

Bayatkashkoli A, Faegh M (2014) Evaluation of mechanical properties of laminated strand lumber and oriented strand lumber made from Poplar wood (Populus deltoides) and Paulownia (Paulownia fortunei) with urea formaldehyde adhesive containing nanoclay. International Wood Products Journal 5(4):192–195

Canada GO (2022) Laminated strand lumber. Canada.Ca. Retrieved 21.05.2023 from https://natural-resources.canada.ca/our-natural-resources/forests/industry-and-trade/forest-products-applications/taxonomy-wood-products/laminated-strand-lumber/23710

Ciesla WM (2002) Non-wood forest products from temperate broad-leaved trees (Vol. 15). Food & Agriculture Org. https://www.fao.org/3/y4351e/y4351e00.htm. Accessed 20 May 2023.

Commission TE (2021) The role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution. European Commission. Retrieved 17th May from https://publications.jrc.ec.europa.eu/repository/bitstream/JRC124374/brief_on_role_of_forest-based_bioeconomy_in_mitigating_cc_online.pdf

Council AHE (2017) American Hardwood Lumber Grades. americanhardwood.org. Retrieved 10th May 2023 from https://www.americanhardwood.org/sites/default/files/publications/download/2017-10/AHEC%20Grading%20Guide_AW_pages_0.pdf

de Almeida TH, de Almeida DH, Gonçalves D, Lahr FA (2021) Color variations in CIELAB coordinates for softwoods and hardwoods under the influence of artificial and natural weathering. Journal of Building Engineering 35:101965

de Carvalho Araújo CK, Salvador R, Moro Piekarski C, Sokulski CC, de Francisco AC, de Carvalho Araujo Camargo, S. K. (2019) Circular economy practices on wood panels: a bibliographic analysis. Sustainability 11(4):1057

Denizli N (1997) Physical and mechanical properties of laminated strand lumber treated with fire retardant. Master of Science Dissertation, College of Environmental Science and Forestry, State University of New York. https://experts.esf.edu/esploro/outputs/graduate/Physical-and-mechanical-properties-of-laminated/99890037904826.

Ding Y, Pang Z, Lan K, Yao Y, Panzarasa G, Xu L, Lo Ricco M, Rammer DR, Zhu J, Hu M (2022) Emerging engineered wood for building applications. Chemical Reviews 123(5):1843–1888

(EAD), E. E. A. D. (2018) Structural composite lumber product: Laminated Strand Lumber (LSL). Retrieved 4th June 2023 from https://www.eota.eu/download?file=/2017/17-13-0308/for%20ojeu/ead%20130308-00-0304_ojeu2020.pdf

Espinoza O, Buehlmann U (2018) Cross-laminated timber in the USA: Opportunity for hardwoods? Current Forestry Reports 4:1–12

Feraboli P (2008) Notched response of OSB wood composites. Compos A Appl Sci Manuf 39(9):1355–1361

Fodor F, Ábrahám J, Németh R (2018) Bonding acetylated hornbeam wood (*Carpinus betulus* L.). Pro Ligno 14(4):10

Fodor FP (2023) Acetylation of European hornbeam (Carpinus betulus L.) wood for outdoor applications. PhD Dissertation, University of Sopron. 1-150. http://doktori.uni-sopron.hu/id/eprint/852/4/Pozsgayn%C3%A9%20Fodor_Dissertation_2023.Text.Marked.pdf

Gao Z, Gong M (2021) Strand-Based Engineered Wood Products in Construction. Engineered Wood Products for Construction. IntechOpen, New York

Gong M (2019) Lumber-based mass timber products in construction. Timber buildings and sustainability. IntechOpen, New York, pp 7–26

Hasan K, Horváth PG, Kóczán Z, Le DHA, Bak M, Bejó L, Alpár T (2021a) Novel insulation panels development from multilayered coir short and long fiber reinforced phenol formaldehyde polymeric biocomposites. J Polym Res 28(12):1–16. https://doi.org/10.1007/s10965-021-02818-1

Hasan KF, Horváth PG, Bak M, Alpár T (2021b) A state-of-the-art review on coir fiber-reinforced biocomposites. RSC Adv 11(18):10548–10571. https://doi.org/10.1039/D1RA00231G

Hasan KF, Horváth PG, Bak M, Le DHA, Mucsi ZM, Alpár T (2021c) Rice straw and energy reed fibers reinforced phenol formaldehyde resin polymeric biocomposites. Cellulose 28:7859–7875. https://doi.org/10.1007/s10570-021-04029-9

Hasan KF, Horváth PG, Zsolt K, Alpár T (2021d) Design and fabrication technology in biocomposites manufacturing. In: Sriariyanun M, Mavinkere Rangappa S, Siengchin S, Homn Nath D (eds) Value-added biocomposites: technology, innovation, and opportunity. CRC Press, New York, pp 158–183

Hasan KF, Horváth PTGR, Alpár T (2021e) Nanotechnology for waste wood recycling. Nanotechnology in Paper and Wood Engineering. Woodhead Publishing, New York

Hasan KF, Horváth PTGR, Alpár T (2021f) Thermomechanical Behavior of Methylene Diphenyl Diisocyanate-Bonded Flax/Glass Woven Fabric Reinforced Laminated Composites. ACS Omega 6(9):6124–6133. https://doi.org/10.1021/acsomega.0c04798

Hasan KF, Xiaoyi L, Shaoqin Z, Horváth PG, Bak M, Bejó L, Sipos G, Alpár T (2022) Functional silver nanoparticles synthesis from sustainable point of view: 2000 to 2023-A review on game changing materials. Heliyon 8(12):e12322. https://doi.org/10.1016/j.heliyon.2022.e12322

Horváth AL, Szakálosné Mátyás K, Horváth B (2012) Investigation of the applicability of multi-operational logging machines in Hardwood stands. Acta Silvatica Et Lignaria Hungarica 8(1):133–144

Hwang K, Komatsu K (2002) Bearing properties of engineered wood products I: effects of dowel diameter and loading direction. J Wood Sci 48:295–301. https://doi.org/10.1007/BF00831350

Institute HS (2016a) MSZ EN 338:2016. Structural timber - Strength classes. In (Vol. MSZ EN 338:2016). Budapest, Hungary

Institute HS (2016b) MSZ EN 14081–1:2016. Timber structures. . In *Strength graded structural timber with rectangular cross section General requirements* (Vol. MSZ EN 14081–1:2016, pp. 42 pp). Budapest, Hungary

Jakob M, Mahendran AR, Gindl-Altmutter W, Bliem P, Konnerth J, Mueller U, Veigel S (2022) The strength and stiffness of oriented wood and cellulose-fibre materials: a review. Prog Mater Sci 125:100916

Jerves R, Yadama V, Aro M, Pelaez-Samaniego MR (2023) Cross-laminated strand veneer lumber mass timber panels from thermally modified strands. Constr Build Mater 368:130370

Khatri P, Sahoo K, Bergman R, Puettmann M (2021) Life Cycle Assessment of North American Laminated Strand Lumber (LSL) Production. Recent Progress in Materials 3(4):1–25

Kim J-H, Choi S-W, Park D-H, Park S-B, Kim S-K, Park K-J, Lee J-M (2018) Effects of cryogenic temperature on the mechanical and failure characteristics of melamine-urea-formaldehyde adhesive plywood. Cryogenics 91:36–46

Klarić S, Obučina M (2020) New trends in engineering wood technologies. New Techno Dev Appl II:5

Krstic M, Vukin M, Bjelanovic I (2010) Basic problems of reclamation of forests of Hungarian and Turkey oak on the territory of Belgrade. For Ecosyst Climate Changes 59:20

Kumar C, Leggate W (2022) An overview of bio-adhesives for engineered wood products. Int J Adhes Adhes 118:103187

Laboratory FP (1987) Wood handbook: wood as an engineering material. The Laboratory, New York

Lin W-S, Lee W-J (2018) Influence of curing temperature on the bonding strength of heat-treated plywood made with melamine-urea-formaldehyde and phenol–formaldehyde resins. European Journal of Wood and Wood Products 76:297–303

Liu W, Yang H, Dong F, Jiang D (2008) Experimental study on fl exural behavior of glulam and laminated veneer lumber beams. Modern Bamboo Structures. CRC Press, New York, pp 171–182

Mahmud S, Hasan KF, Jahid MA, Mohiuddin K, Zhang R, Zhu J (2021) Comprehensive review on plant fiber-reinforced polymeric biocomposites. J Mater Sci 56:7231–7264. https://doi.org/10.1007/s10853-021-05774-9

Maleki S, Najafi SK, Ebrahimi G, Ghofrani M (2017) Withdrawal resistance of screws in structural composite lumber made of poplar (Populus deltoides). Constr Build Mater 142:499–505

Mayo J (2015) Solid wood: case studies in mass timber architecture, technology and design. Routledge, New York

Merela M, Čufar K (2013) Density and mechanical properties of oak sapwood versus heartwood in three different oak species. Drvna Industrija 64(4):323–334

Minnie (2023) *Wood Beam - Laminated Strand Lumber (LSL)*. Last accessed 20 May 2023 https://www.dimensions.com/element/wood-beam-laminated-strand-lumber-lsl

Molnár S., F. P., Börcsök Z., Zoltán G. (2016). Földünk ipari fái (Industrial trees of Earth). ERFARET Kft. Sopron, 48–50

Molnar S (2008) The Present Situation of Hungarian Forest Based Industry. 2008 International Conference on Intelligent Engineering Systems

Monlar Sandor BM (2002) Turkey Oak, Hornbeam, Beech, and Domestic Poplar. In K. Ildiko (Ed.), *Wood species of Hungary*. Szaktudas Kiado Haz Rt

Moradpour P, Pirayesh H, Gerami M, Jouybari IR (2018) Laminated strand lumber (LSL) reinforced by GFRP; mechanical and physical properties. Constr Build Mater 158:236–242

Moradpour P, Behnia M, Pirayesh H, Shirmohammadli Y (2019) The effect of resin type and strand thickness on applied properties of poplar parallel strand lumber made from underutilized species. Eur J Wood Prod 77:811–819

Mumma T (1995) Re-evolution of resource efficient housing and The guide to resource efficient building elements University of Montana]. Missoula, Montana, USA. https://scholarworks.umt.edu/cgi/viewcontent.cgi?article=4398&context=etd

Olorunnisola AO, Olorunnisola AO (2018) Uses of Wood and Wood Products in Construction. Design of Structural Elements with Tropical Hardwoods. Springr, Cham, pp 71–92

Porteous J, Kermani A (2013) Structural timber design to Eurocode 5. Wiley-Blackwell, West Sussex, United Kingdom.

Rämäkkö M (2021) Architectural language of tall wood buildings: Structural Solutions for Architectural Language of Tall Wood Buildings. Master's Dissertation, Tampere University. https://trepo.tuni.fi/bitstream/handle/10024/131390/R%C3%A4m%C3%A4kk%C3%B6Marharyta.pdf?sequence=2

Rockwood D, Naidu C, Carter D, Rahmani M, Spriggs T, Lin C, Alker G, Isebrands J, Segrest S (2004) Short-rotation woody crops and phytoremediation: opportunities for agroforestry? New Vistas in Agroforestry: A Compendium for 1st World Congress of Agroforestry, 2004

Romagnoli M, Fragiacomo M, Brunori A, Follesa M, Scarascia Mugnozza G (2019) Solid wood and wood based composites: The challenge of sustainability looking for a short and smart supply chain. Digital wood design: innovative techniques of representation in architectural design, pp. 783–807

Sandberg D, Gorbacheva G, Lichtenegger H, Niemz P, Teischinger A (2023) Advanced Engineered Wood-Material Concepts. Springer

Handbook of Wood Science and Technology. Springer, New York, pp 1835–1888

Seth M (2003) Trees and their economic importance. Bot Rev 69(4):321–376

SFS Group USA I (2023) Guide to Composite Lumber — OSB vs. LSL vs. LVL vs. PSL vs. Glulam. SFS Group. Retrieved 17th May from https://us.sfs.com/learn-more/composite-lumber-comparisons

Smith WR, Wu Q (2005) Durability improvement for structural wood composites through chemical treatments: current state of the art. For Prod J 55(2):8

Sun X, He M, Li Z (2020) Novel engineered wood and bamboo composites for structural applications: State-of-art of manufacturing technology and mechanical performance evaluation. Constr Build Mater 249:118751

Sun X, He M, Liang F, Li Z, Wu L, Sun Y (2021) Experimental investigation into the mechanical properties of scrimber composite for structural applications. Constr Build Mater 276:122234

Tripathi J, Rice RW (2017) Thermal conductivity values for laminated strand lumber and spruce for use in hybrid cross-laminated timber panels. BioResources 12(4):8827–8837

Van Acker J, Defoirdt N, Van den Bulcke J (2016) Enhanced potential of poplar and willow for engineered wood products. Proceedings of the 2nd Conference on Engineered Wood Products Based on Poplar/Willow Wood. León, Spain

Van Acker J (2021) Opportunities and challenges for hardwood based engineered wood products. Hardwood Conference, 9th, Proceedings, part 2. In Hardwood Conference Proceedings p.5-14

Vladimirova E, Gong M (2022) Veneer-Based Engineered Wood Products in Construction. In Engineered Wood Products for Construction (pp. 39–62)

Vnučec D, Kutnar A, Goršek A (2017) Soy-based adhesives for wood-bonding–a review. J Adhes Sci Technol 31(8):910–931

Vukin M, Rakonjac L (2013) Comparative analysis of some bioecological characteristics of Hungarian oak and Turkey oak. Archives of Biological Sciences 65(1):331–340

Walker JC, Kretschmann DE, Hernandez R (2006) Grading timber and glued structural members. Primary Wood Processing: Principles and Practice. Springer, Dordrecht, The Netherlands. p. 339–390

Wang Z, Gong M, Chui Y-H (2015) Mechanical properties of laminated strand lumber and hybrid cross-laminated timber. Constr Build Mater 101:622–627

Worrell R (1995) European aspen (Populus tremula L.): a review with particular reference to Scotland I. Distribution, ecology and genetic variation. For Int J for Res 68(2):93–105

Ye H, Wang Y, Yu Q, Ge S, Fan W, Zhang M, Huang Z, Manzo M, Cai L, Wang L (2022) Bio-based composites fabricated from wood fibers through self-bonding technology. Chemosphere 287:132436

Zeug W, Bezama A, Thrän D (2022) Application of holistic and integrated LCSA: case study on laminated veneer lumber production in Central Germany. Int J Life Cycle Assess 27(12):1352–1375

Zhang Y, Guan P, Zuo Y, Li P, Bi X, Li X (2023) Preparation of highly-densified modified poplar wood by evacuating the micropores of wood through a gas expansion method. Ind Crops Prod 194:116374