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Edited by Xiaojian Zhou

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IntechOpen Book Series

Industrial Engineering and Management

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Aims and Scope of the Series

Industrial Engineering and Management (IEM) is a discipline that focuses on optimizing complex processes and systems within various industries. It involves the integration of engineering, business, economics, mathematics, and behavioral sciences to improve efficiency, productivity, quality, and overall performance in organizations. Key aspects of Industrial Engineering and Management include: Process Optimization; System Analysis and Design; Quality Control and Management; Supply Chain Management; Operations Management; Human Factors and Ergonomics; Project Management; Cost Analysis and Financial Management; Decision Analysis.

Overall, Industrial Engineering and Management aims to optimize resources, improve processes, enhance productivity, and ensure the effective and efficient utilization of all elements involved in the production or delivery of goods and services. It is crucial in today's competitive business environment for organizations to stay efficient and competitive.

Production Engineering and Operational Excellence are fields of study and practices that focus on optimizing and improving the manufacturing and production processes within an organization. It combines principles from engineering, management, and operational strategies to enhance productivity, efficiency, quality, safety, and sustainability in the production of goods and services.

Here are the key components of Production Engineering and Operational Excellence: Process Optimization; Operational Excellence; Manufacturing Systems Design; Quality Management; Supply Chain Optimization; Production Planning and Scheduling; Automation and Technology Integration; Health, Safety, and Environmental Management; Cost Management; Performance Measurement and Key Performance Indicators (KPIs); Continuous Improvement and Innovation.

Production Engineering and Operational Excellence are crucial for organizations aiming to stay competitive in the global market by achieving high levels of efficiency, quality, and customer satisfaction while optimizing resources and minimizing waste. It is a multidisciplinary approach that encompasses engineering principles, management strategies, and the effective use of technology to drive operational success.

Meet the Series Editor

Fausto Pedro Garcia Marquez is a Full Professor at UCLM, Spain, with accreditation since 2013. He also holds the position of Honorary Senior Research Fellow at Birmingham University, UK, and serves as a Lecturer at the Postgraduate European Institute. In addition to these roles, Fausto has experience as a Senior Manager at Accenture from 2013 to 2014. He earned his European Ph.D. with the highest distinction. Throughout his career, Fausto has received numerous awards and honors. These include the Nominate Prize (2022), Gran Maestre (2022), Grand Prize (2021), Runner Prize (2020), and Advancement Prize (2018), as well as Runner (2015), Advancement (2013), and Silver (2012) by the International Society of Management Science and Engineering Management (ICMSEM). He was also the recipient of the First International Business Ideas Competition 2017 Award. Fausto's contributions extend to academic publishing, with over 242 papers to his name. Notably, his work has been recognized in journals like "Applied Energy" (Q1, IF 9.746, Best Paper 2020) and "Renewable Energy" (Q1, IF 8.001, Best Paper 2014). His affiliations include the editorial and authorship roles in more than 50 books, with publications through respected publishers such as Elsevier, Springer, Pearson, Mc-GrawHill, IntechOpen, IGI, Marcombo, and AlfaOmega. He has authored over 100 international chapters and holds 6 patents. Fausto serves as the Editor of 5 International Journals and is a Committee Member for more than 70 International Conferences. His research portfolio encompasses being the Principal Investigator in 4 European Projects, 8 National Projects, and participating in over 150 projects involving universities and companies. His areas of expertise and research interests span Artificial Intelligence, Maintenance, Management, Renewable Energy, Transport, Advanced Analytics, and Data Science. Fausto is a recognized Expert in the European Union in AI4People (EISMD) and ESF. He also serves as the Director of www.ingeniumgroup.eu, holds the status of Senior Member at IEEE since 2021, and has been honored as an Honorary Member of the Research Council of the Indian Institute of Finance since 2021. Fausto is also the Committee Chair of The International Society for Management Science and Engineering Management (ISMSEM) since 2020.

Meet the Volume Editor

Dr. Xiaojian Zhou is a Full Professor at Southwest Forestry University in China. He is experienced in bio-based resin adhesives and composites. The EU, National Natural Science Foundation of China (NSFC), and other funding have supported his research. He has published more than 100 articles and conference papers, as well as five books and chapters, both domestic and international. He has served as a reviewer for multiple international journals and obtained 20 authorized rights for invention patents. Additionally, he has received five S&T awards as a main contributor. As an outstanding youth representative, he obtained the Yunnan Provincial Youth S&T Award and the National Forest and Grass Youth S&T Award, as well as the special allowance from the Yunnan Provincial People's Government. He was selected as a high-level national and provincial talent in recent years.

Contents

Preface

As one of the most important renewable and sustainable material resources, wood has been widely used in daily life for thousands of years and represents a bridge between tradition and modernity, as well as changing people's lives in different ways.

This book aims to present the development of the wood industry in different regions, especially introducing the representative countries or regions, for example, Europe, Asia, Africa, North America, and South America. Also, it will present the traditional and currently advanced wood industry development situation from the past, present, and future, such as advanced functional wooden composites, from traditional wood timber utilization, to currently popular wood-based panels, wooden buildings, wood bio-energy, wood-carbon stock, wood-biodiversity of nature value, including light-weight & mass-weight wooden materials, use of alternative fast-growing species/recycled wood, new adapted process to hardwoods and softwood, and many others. Wood is used in every possible unit size, from macro-to micro- and even nano-scale.

In addition, the most recent research achievements in super wood products with various functionalities, utilizing advanced and novel techniques in high-added-value fields, will also be covered.

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Chapter 1

Woodworking Techniques in Ancient Egypt

Medhat Abdallah Abd Elhamid

Abstract

Timber was extensively used in manufacturing ancient Egyptian daily life items and funerary furniture. This chapter focuses on the woodworking techniques and carpentry tools in ancient Egypt that are well known through the wall painting scenes of the ancient tombs, and the model of the carpentry workshop dates back to the Middle Kingdom, in addition to the excavation finds. The ancient Egyptian carpenters used many types of wood, including indigenous trees (Acacia sp., sycomore fig., and Tamarisk sp., etc.) and foreign trees (cedar, cypress, and Juniper sp., etc.). This chapter illustrates the types of these trees and their wood properties and uses. The techniques of woodwork include pending, plywood, drilling, turning, and smoothing, in addition to the wooden joints (corner joints, butt joints, mortise and tenon joints, dovetail joints, scarf joints, etc.). The ancient Egyptians developed several methods for fittings and fixtures, such as nails and tacks, hinges, brackets, and locks. The author sheds light on methods of repairing wooden artifacts and the reuse of earlier wooden artifacts, as well as the materials used in decorating wooden artifacts, including painting materials, leather, varnish, inlay, bark, gilding, plating, etc.

Keywords: woodworking, ancient Egypt, wood species, joints, funerary furniture, carpentry tools, decorating wood

1. Introduction

Wood is one of the most commonly used natural materials in ancient Egypt. The findings of excavations proved that the ancient Egyptians utilized wood to manufacture daily life items and funerary furniture. Most of the indigenous trees produce wood of either small or poor quality. The ancient Egyptians soon realized the necessity of importing high-quality wood from neighboring countries. The Palermo Stone dates back to the 4th dynasty and states that Egypt imported 40 ships laden with timber from adjacent countries during the reign of *Snefru*. The Egyptian carpenters determined through experience and practical work the capacities of each wood and that each timber has an individual quality of work. This experience and awareness are shown by the intentional selection of specific wood types for furniture and coffins' long boards or plank wood, such as sycomore fig, cedar, and juniper, while other solid and durable types are used for interconnecting elements, such as Nile acacia, Christ's thorn, or sidder.

In ancient Egypt, the crafts of carpentry and joinery, along with wood carving, were highly valued. They had attained a high level of skill by the time of the Old

Kingdom, which lasted from roughly 2980 to 2475 B.C. Those skills have been developed through ancient Egyptian history and influenced by the economic and political state. The woodworking techniques and tools can be identified by the scenes depicted on the mural paintings and reliefs of tombs in ancient Egypt, as well as the artifacts and tools found during excavation missions.

2. The types of wood in ancient Egypt and their sources

2.1 The indigenous wood

The large-scale wood planks produced from indigenous trees were rare in ancient Egypt. The scarcity of wood and indigenous trees, which are generally of poor quality, was a challenge faced by the carpenters at the time of the pre-dynasty; they could only convert the indigenous wood into short-length boards. The scenes of trees on mural paintings in the tombs and temples, besides the fruits and twigs found in the tombs, suggested that the common native trees employed by the carpenters in ancient Egypt were sycomore fig, acacia, and tamarisk, though the wood of other trees was sometimes used, especially that of willow, Persea, and Christ's thorn, as well as date palm and doum palm.

2.1.1 Acacia [Vachellia sp. (Leguminosae: Mimosoideae)]

Thorn trees, or acacias, are a genus of flowering plants in the legume family, *Fabaceae*. Acacia wood has been utilized in Egypt since the pre-dynasty. Many acacia species grow in Egypt, for instance, *Vachellia nilotica*, *Vachellia albida*, and *Vachellia tortilis*. Fruits, twigs, stems, and roots of acacia are found in tombs. Acacia blossoms have been identified in garlands and floral collars [1–3].

Acacia wood is strong, heavy, and dense, with high durability, and the heartwood is red. Moreover, acacia wood has very high bending and compression strengths [2].

Acacia wood was widely used in ancient Egypt and favored for carving statues, boatbuilding, doors, tenons, dowels, and construction work (the tree trunks used for supporting the ceiling of the burial shaft of step pyramid in the Saite era are identified as *Vachellia nilotica*).

2.1.2 Sycomore fig [Ficus sycomorus L. (Moraceae)]

The sycomore fig tree grows throughout Egypt, both lower and upper Egypt, as well as in oases. The sycomore fig tree is widely depicted on the walls of tombs and mentioned in literature and religious texts [1–3].

Fig wood is of medium quality; it is pale, light, fibrous, coarse, and easy to carve. Fig wood is vulnerable to insect damage, but this disadvantage can be somewhat offset if manufactured wood is extensively painted and embellished [2, 4].

The wood of sycomore trees is widely used in making coffins, small naoses, votive statuettes, and the small wooden models often found in tombs.

2.1.3 Tamarisk [Tamarix sp. (Tamaricaceae)]

Tamarisks are evergreen or deciduous shrubs or trees growing to 1–18 m in height and forming dense thickets. Tamarisks are indigenous trees; there are many tamarisk species in Egypt, such as *T. aphylla*, *T. articulate*, and *T. nilotica*; other species of shrub-like trees are also indigenous to Egypt [2, 5].

The tamarisk is mentioned in the ancient texts, from the Old Kingdom onward. The wood of tamarisk is light, coarse, dense, with medium to poor quality, prone to insect damage, and knotty, but it is easy to carve and can be serviceable if painted [2, 4].

Tamarisk wood is usually used for carving small statues and making tenons and dowels; it is also used sometimes for making small beds, coffin plank segments, and inserts.

2.1.4 Sidder or nabk [Ziziphus sp. (Rhamnaceae)]

Sidder, or nabk in Arabic, is also known as Christ's Thorn (*Ziziphus spina-christi* L.), Lotus Tree, Wild Jujube, and Lotus Jujube (*Ziziphus lotus* L.). The sidder or nabk trees are native to Egypt; both fruits and wood were used in Egypt. The fruits of nabk are well known in Egypt from pre-dynasty times onward [1, 3, 5].

The wood of nabk is hard, durable, and considered a good-quality working material. The nabk tree is not large enough to provide long planks [2, 5].

The wood of these trees is usually used for making the interconnecting elements (tenons and dowels), and the sidder wood is used from time to time for making the coffin planks.

2.1.5 Willow [Salix sp. (Salicaceae)]

Willow is a small tree or branched shrub [5] found on the Nile banks and islands of the river Nile [1, 3]. Leaves of willow trees were used for making funerary garlands [1]. The utilization of willow wood in ancient times was limited; it may be that the wood's utility is restricted by the tree's short stature.

The wood of willow is white, smooth, perishable, and non-splintering [2]. The ancient Egyptians used willow for several purposes: boxes, bowls, chariots, and small domestic items.

2.1.6 Persea [Mimusops laurifolia and Mimusops Schimperi (Sapotaceae)]

The persea evergreen tree belongs to the laurel family and is a medium-sized tree [2], 15–30 meters in height. The persea tree was mentioned in Egyptian texts from the 18th dynasty onward [1].

The wood of persea is light brown to whitish with a yellow tint [2].

The wood of the persea tree (*Mimusops Schimperi*) was used occasionally. For instance, a headrest from the New Kingdom has been identified as being made of persea [1].

2.1.7 Almond [Prunus dulcis (Miller) (Rosaceae)]

A deciduous tree, up to 8 m high and sometimes with spine-tipped twigs (especially in wild plants), is native to Central and Northwest Asia [2, 5].

The almond heartwood is reddish-brown, close-grained, strong, and hard [2]. The wood, used in making walking sticks from Thebes, dates back to the 18th dynasty [1].

Although the trees of carob (*Ceratonia siliqua*), Egyptian myrobalan or Egyptian balsam (*Balanites aegyptiaca*), Assyrian plum (*Cordia myxa*), date palm (*Phoenix dactylifera*), and doum palm (*Hyphaene thebaica*) were cultivated in ancient Egypt, most of those species had relatively limited use in woodworking.

2.2 The foreign wood

Although the ancient Egyptians used Indigenous trees for various purposes, sources of Indigenous wood were limited by their natural reluctance to fell trees, which were valuable for their fruit-bearing capacity and shade-giving properties as well. In addition, the indigenous trees could not provide planks and beams of the size and quality required for the carpentry and joinery works.

Because of the expanding demand for wood and the enhancement of woodworking techniques and tools, Egyptians turned out to import timber from neighboring countries that had high resources of high-quality timber and already had trade relations with Egypt.

The fact that timber was being imported as early as the 1st dynasty is not surprising. The oldest surviving written evidence of an international timber trade is the Palermo stone, in which *Snefru*, the first pharaoh of the 4th dynasty, tells of importing cedar from Lebanon.

2.2.1 Cedar [Cedar sp. (Pinaceae)]

Three species of true cedar trees belong to the *Cedrus* family: the cedar of Lebanon (*Cedrus libani*), the Atlas cedar (*Cedrus atlantis*), and the Indian cedar (*Cedrus deodara*), probably used in ancient Egypt. Although the woods of the Lebanon and Atlas cedars cannot be distinguished from each other microscopically, it may be accepted that any cedar wood found in Egypt is *Cedrus libani*. Cedar wood was used in Egypt as early as the pre-dynasty; it was evidently being imported into Egypt at that early date. Cedar wood, which may be the earliest imported wood to Egypt, was widely common in ancient Egypt from pre-dynasty onward to Greco-Roman times [1, 4].

The cedar of Lebanon is a large tree; it can reach 40 m in height and 1–2 m in diameter. The native range of *Cedrus libani* is from Lebanon to Turkey and Cyprus [2, 5]. Cedar wood is pinkish-brown, aromatic heartwood characterized by high durability against microorganisms and resistance against insect infections. Cedar wood is considered one of the most valuable woods for construction because of its high degree of dimensional stability, structural efficiency, good resistance to shock loads, and bending strength, in addition to its durability, straight-grained nature, and good polishing properties [2, 4].

The cedar wood was used for various purposes, including boatbuilding, the construction of shrines [6], funerary furniture, boxes, coffins, statuary making, and construction elements.

2.2.2 Cypress [Cupressus sempervirens L. (Cupressaceae)]

The Mediterranean cypress tree is an evergreen, resinous, and medium-to-large tree, 30–50 m in height, with a trunk 1–3 meters in diameter. Although classical writers mentioned that the cypress tree may have been cultivated in Egypt in the Pharaonic era, and some specimens of it grow in the Delta (Lower Egypt) at the present day, the cypress is not an indigenous tree and probably imported to Egypt. Perhaps the cypress wood fragment from the pre-dynasty era that was found in the same location as cedar fragments suggested that the cypress was imported from Syria [1–3, 5].

The wood of the Mediterranean cypress is reddish-brown, even-grained, smooth, aromatic, and durable, as well as taking a good polish [2].

The cypress wood was used in furniture, coffins, and construction.

2.2.3 Juniper [Juniperus sp. (Cupressaceae)]

Many juniper trees that yield timber in South Europe and Southwestern Asia, such as *J. phoenicea* (Mediterranean region), *J. excelsa* (South-Eastern Europe and from Asia Minor to Pakistan), *J. drupacea Labill* (Greece, Asia Minor, Syria, Lebanon), and *J. foetidissima* (Greece, Asia Minor, Lebanon) are very similar in many anatomical characteristics. The distinction between certain species is very difficult, and any of them could have been used in ancient Egypt [1–2, 5].

The wood of the juniper is reddish-brown, hard, smooth, aromatic, and durable, as well as taking a good polish [2].

The juniper wood was used in furniture, boxes, boatbuilding, and coffins.

2.2.4 Aleppo pine [Pinus halepensis Mill. (Pinaceae)]

Aleppo pine is a slender, small to medium-sized tree, 15–30 meters in height, with a trunk diameter of up to 60 cm. Aleppo pine (also known as Jerusalem pine) grows in Syria and Asia Minor, and Aleppo pine is considered the most common pine in the Mediterranean region [2, 5].

The wood of Aleppo pine is resinous and relatively strong, but less so than that of some other species. The wood is used in coffins and construction [2].

2.2.5 Elm [Ulmus sp. (Ulmaceae)]

The elm tree is medium-to-large, usually 20 meters or more in height. The common elm (*U. campestris*) is widely distributed in Europe and Asia, including Western Asia, Asia Minor, and Northern Palestine, one of which places it doubtless imported to Egypt from these regions [2, 5].

The wood of elm was used in making the chariots in ancient Egypt; identified specimens of Tutankhamun chariots may be *U. minor* [1].

The heartwood of elm is pale to reddish-brown, tough, and durable when permanently wet. Because the steam-bending properties of the timber are superior to those of ash, along with the timber's inherent toughness and hardness, ancient wheelwrights found it perfect for use in the construction of chariot bodies, wheels, spokes, and axles [2].

2.2.6 Common yew [Taxus baccata L. (Taxaceae)]

Evergreen trees up to 15 meters high, with broad crowns and reddish-brown bark, Common yew grows in Europe, North Africa, and Western Asia, only on mountains in the Mediterranean region [2, 5].

Yew is moderately even-grained, is the densest of the conifers, and has pale sapwood with high tensile strength and a distinctive reddish-orange to russet heartwood color that withstands compression. The yew wood is heavy, hard, durable, and fine-textured grains [2].

The yew wood is commonly used in coffin construction and statues; besides, the yew is an ideal material for carving.

2.2.7 Cilician fir [Abies cilicica (Pinaceae)]

Cilician fir, or Taurus fir, is a species of conifer up to 30 meters in height that grows on mountains above sea level in Lebanon, Syria, and Turkey [5].

Although the papyri (Zenon archive; Tebtunis) mentioned cultivating fir trees and conifers in Egypt during the Ptolemaic period, the translation of those papyri should be reconsidered since the Cilician fir inhabits the mountains, does not tolerate the hot temperatures, and would not have survived in the Egyptian climate [1, 2].

The fir wood is yellowish-white, easily split, flammable, and perishable. The Cilician fir wood was used for merchant and boatbuilding (masts), religious ceremonies, day-life activities, woodworking, and mummy portraits.

2.2.8 Silver birch [Betula pendula Roth. (Betulaceae)]

Silver or European White birch is a medium-sized, 15–25-meter-high deciduous tree that owes its common name to the white peeling bark on the trunk. The tree grows across Europe, Northern Greece, and the Caucasus [2, 5].

The birch wood is pale in color, with light reddish-brown heartwood and inconspicuous heartwood that is moderately hard and strong but perishable [2].

Birchwood was not common in ancient Egyptian woodworking; strips of bark were used for covering some artifacts in the tomb of Tutankhamun, for example, staves, bows, and the box of bows [1, 3].

2.2.9 Lime [Tilia europaea (Tiliaceae)]

The European lime, also known as the common lime tree, is a large deciduous tree up to 15–50 meters in height with a trunk up to 2.5 meters, native to Middle and Southern Europe, from where the wood might easily have reached Egypt [2, 5].

Lime wood is yellowish-white to pale brown, soft and easily worked wood, fine grains, and perishable. The wood of lime is used in coffins and mummy portraits [1, 2].

2.2.10 Ebony [Dalbergia melanoxylon (Leguminosae—Papilionoideae)]

Ebony or African Blackwood (*Dalbergia melanoxylon*), called in ancient Egypt hbny, is a small tree, reaching 4–15 meters in height, with gray bark and spiny shoots, native to seasonally dry regions of Africa from Senegal east to Eritrea, to the southern areas of Tanzania to Mozambique, and south to the northeastern parts of South Africa and Western India [2].

The ancient Egyptian texts mentioned that ebony was acquired through trade with Egypt's southern neighbors (Genebteyew, Kush, Negro Land, Nubia, Punt, and the South Countries). Logs of this wood are seen being readied to load onto one of Hatshepsut's ships in the Punt reliefs from her memorial temple at Deir el-Bahri [1, 3].

Based on its characteristic color and appearance, ebony wood can be readily recognized without microscopic examination. The ebony wood is lustrous and ranges in color from reddish to pure black; the heartwood is almost black, contrasting with the pale sapwood, with dense grains, very hard, very heavy, resistant to attack by insects, durable, and difficult to work but taking a good polish [2].

Ebony is one of the main ornamental and decorative sources used to cover and decorate wood. It is also used in making furniture, inlay, staves, veneer, and sculpture.

2.2.11 Turkey oak [Quercus cerris L. (Fagaceae)]

Turkey oak is a large deciduous tree growing to 25–40 meters in height with a stout trunk up to 2 meters in diameter, native to South-Eastern Europe and Asia Minor. Theophrastus and Pliny stated that the cork oak grew in the vicinity of Thebes; the cork oak occurs in the Western Mediterranean region [2, 5].

Although the oak is not as high-quality as some other species, the heartwood is sturdy, strong, and long-lasting, with a light tan or brown color [2].

The oak wood has been used for construction, furniture, and joinery. It seems that oak was used in limited quantities in ancient Egypt. The Royal Botanic Gardens in Kew identified a specimen of wood from one of the dowels of the large gilt shrines that enclosed the sarcophagus of Tutankhamun as oak [1, 3]. There is no concrete evidence for utilizing oak on a large scale in ancient Egypt.

2.2.12 Common box [Buxus sempervirens L. (Buxaceae)]

Evergreen trees or shrubs, up to 10 m in height, with glabrous, tetragonal shoots, usually have several slender trunks covered with thin gray bark; grow in Europe, Western Asia, and North Africa [2, 5]. The utilization of the common box dates back to the Middle Kingdom and onward to the Greco-Roman period [1].

The common boxwood is golden-yellow with inconspicuous heartwood and is strong, hard, heavy, and close-grained [2].

The wood of the box is used in tool handles, knife handles, sculpture, inlay, and domestic items [1].

2.2.13 Olive [Olea europaea L. (Oleaceae)]

The olive tree, a small evergreen tree 2–10 m in height, is widespread in the Mediterranean region [5].

The wood of the olive is mottled brown, sometimes with decorative figures, hard, heavy, strong, and durable [2].

The olive wood was not utilized on a large scale owing to the old tree becoming hollow, so branches of fewer diameters are used to obtain wood from trees no longer required for fruit production. In ancient Egypt, a wood from stelae dating back to the late period (and possibly the Roman period) was identified as *Olea europaea* L. [1].

2.2.14 Plum [Prunus domestica L. (Rosaceae)]

Deciduous shrub or tree, up to 6–10 m in height with brownish bark, grows in Europe, Western Asia, and North Africa [5].

The wood plum is similar to almond wood; it is difficult (maybe not possible) to distinguish the wood with any certainty from almond using anatomical characters, the almond being more likely in Egypt [1, 2].

The wood used in making the spokes of the chariots (Florence Museum) dates back to the 18th dynasty [1].

2.2.15 Common ash [Fraxinus excelsior L. (Oleaceae)]

Large-sized trees, up to 45 m in height, commonly known as European ash, are distributed widely throughout Europe to the Caucasus [2].

Common ash is usually a white timber that darkens to a creamy brown with good seasoning qualities and little possibility of splitting; it is a very tough timber with excellent steam-bending properties, strong and resilient, but perishable [2].

The wood of ash was identified in a composite bow (*F. excelsior*), and the axle, felloes, and frame of the floor of the chariot date back to the 18th dynasty (*F. ornus*) (Florence Museum), as well as an arrow dating back to the 26th dynasty [1].

2.2.16 Storax tree [Liquidamber orientalis (Miller) Hamamelidaceae]

A medium to large deciduous tree up to 30 m in height, the storax is restricted to the islands of Rhodes and Cos and the adjacent Turkish mainland [2].

The storax wood is brown and closed-grained [2]. The storax balsam was used in ancient Egypt for making perfumery and embalming. The only specimen of a small piece of (*Liquidamber orientalis*) was found in the tomb of Tutankhamun; its connections and purpose are unknown [1].

2.2.17 European beech [Fagus sylvatica (Fagaceae)]

The European beech, or common beech, is a large, graceful deciduous tree up to 50 meters in height [2].

The beech wood is a pale straw color, sometimes with a pink or brown hue, with strong, hard, fine, and short grains, good workability, and resistance to compression and spitting [2].

European beech is not common in ancient Egypt; Lucas stated that using it in making a mummy label dates back to the 3rd–4th century AD [1].

2.2.18 Field maple [Acer campestre L. (Aceraceae)]

The field maple is a small flowering tree up to 15 meters in height and is often shrubby. The native range of field maple includes much of Europe and Southwest Asia, from Turkey to the Caucasus, and North Africa in the Atlas Mountains [2].

The wood of field maple is hard and strong, fibrous, very lightweight, and durable [2]. The use of field maple in making part of the frame of the floor of the chariot dates back to the 18th dynasty (Florence) [1].

3. The ancient Egyptian kit of carpentry tools

Ancient Egyptians began practicing woodworking in the early Badarian period (c. 5500–4000 B.C.). They demonstrate that the ancient Egyptians knew and understood cutting tools, even if they did not make furniture. Many of the instruments that were employed throughout the dynastic period had pre-dynastic roots.

During the dynastic period, the carpenters developed a full kit of tools; the scenes of carpentry and woodworking techniques depicted in the walls of the tombs, for example, the scene of carpenters on the tomb of *Sekhem-Ka-Ra* at Giza, 4th dynasty, the tomb of Ti at Saqqara, 5th dynasty, and the tomb of *Rekh-Me-Ra* at Thebes, 18th dynasty (**Figure 1**) [7], as well as models of carpentry workshops and the actual specimens of tools, either full size or miniature, that have been found in the tombs, for example, the carpenters' workshop from *Meketra* tomb, 11th dynasty, illustrated the tools used in woodworking in ancient Egypt.

Figure 1.
Carpentry workshop scene (after Davies, Rekh-Me-Ra*, tomb, 18th dynasty, Thebes, plates, LII, LIII, LV).*

3.1 Adzes

Adzes are essentially flat chisels with a broad, straight cutting edge that are mounted on the end of a hooked wood handle. Woodworkers used adzes to shape and smooth wooden surfaces as well as cut and trim rough wooden boards. The copper-bladed adze appeared before the dynastic age, usually as small bladed tools with straight edges. The shape of the metal blade was developed during the dynastic period, and it occasionally had a blade that cut in both directions, but generally only on one side. The blade is secured to a wooden handle using leather straps that are immersed in water, and when they dry, these straps are tightened over the handle and connect the adze's parts. Linen straps or ropes are usually used to secure the attachment of the blade to the wooden hand.

Adzes were made in a variety of sizes, with small ones (**Figure 2a**) being used to shape wood and larger ones (**Figure 2b**) to remove bark and true timber after it had been converted [1, 8, 9].

3.2 Awl

Awl (**Figure 2c**) may have been used to mark the locations for drilling or to bore holes in thin sheets of wood. The blade is formed from square-section metal, and the grip is composed of beautifully polished wood. The awl's tip may have been sharpened continually; microscopic grinding marks could be seen surrounding it [8].

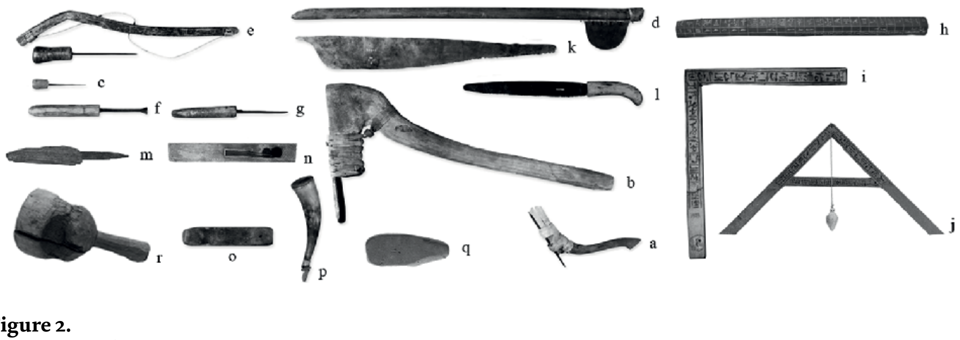

Figure 2.
Carpentry tools in ancient Egypt.

3.3 Axes

Axes (**Figure 2d**) are essential tools developed in the 1st dynasty and are principally used for felling and trimming trees, and occasionally for roughly shaping the wood into planks. The axe consisted of a long wood handle and a curved cutting blade made of bronze or copper alloy. The blade was secured to a wooden handle using leather straps that were tightened over the handle and connected the blade to the axe handle. Axes are of three primary varieties.

1. Axes with a simple, curved blade.

2. Axes where the axe shaft had two lugs affixed to it.

3. Axes that included sockets that let the shaft go through the edge. These axes were invented later and cast in bronze, which flows easier around the sand cores required to create the mold's socket hole.

During the dynasty period, the first kind of axe appears to have been the most often employed as a carpenter's tool. The 1st dynasty's improved copper casting capabilities and the requirement to cut down larger trees to produce larger furniture items led to the invention of the axe [1, 8–10].

3.4 Bow drill

The ancient Egyptian carpenters used small engraving tools and bow drills (**Figure 2e**) for drilling the wood. During the pre-dynastic period, chisels for drills were made of flint; as early as the 1st dynasty, these blades were made of metal; the latter was long, thin, and straight with square or rectangular cross-sections and rounded wooden handles at the top that would fit comfortably in the carpenter's hand.

Although the depiction of a bow drill has appeared for the first time on the reliefs of *Ti* tomb, 5th dynasty at Saqqara, maybe a bow drill was used early for drilling the large holes that pierce the bovine-shaped legs of early dynastic bed frames and furniture items.

The bow drill consists of two components: a bow and an engraving or drilling chisel. Old Kingdom bow drills were made of conveniently shaped branches, which had a slight elbow; at the short end, a cord was fastened to a hole, while at the long end, the cord was looped over a lug. New kingdom bows had holes at each end through which the bowstring was tied; they were much longer and therefore turned the drill more efficiently [8–10].

3.5 Chisels

Chisels were the primary tools in the kit of carpentry in ancient Egypt. Although some chisels were made of metal without a handle, most of the chisels consisted of two parts: the handle and the blade. Both firmer and mortise chisels have been used in the Pharaonic period:

- The firmer chisel (**Figure 2f**) had a handle with a rounded top, which would fit comfortably into the palm of the carpenter's hand, suggesting it was used for handwork and carving; its blade was rectangular in section; and in general, firmer was shorter in length than the mortise chisel.

- The mortise chisel (**Figure 2g**), as this chisel is used for mortising, was struck with a wooden mallet. The handle was large and cylindrical, with flat tops. The blades were square in section to prevent them from bending when chips of wood were prized out of deep mortise [8–10].

3.6 Measuring tools

Egyptian carpenters used measuring tools to ensure the accurate proportions of their artifacts and that they were free of any defect that would spoil their appearance, in addition to reducing the effort expended and the loss of wood during manufacturing. Measuring set included:

- Rulers (**Figure 2h**): they were used to determine the lengths and sizes of the wooden boards used in making various artifacts. They were made either of wood or stone with a rectangular section. Some of them reached the length of a cubit (52.5 cm). They were distinguished by symmetrical spacing and were sometimes engraved or written on them in black ink.

- Try square (**Figure 2i**): although try square is widely used in the New Kingdom, its origin is uncertain. It is made of two key parts: the blade (also known as a beam or tongue) and the stock. It was used in drawing and measuring the right angles to determine the straightness of the edges.

- Linear or string scales have been used in both fine and regular carpentry and construction work since the early Old Kingdom. For example, a plumb bob (**Figure 2j**) was used to ensure that the construction was vertical [8–10].

Threads were used to measure boards and wooden pieces, as well as to assist in carpentry operations, including bending and adjusting the hulls of boats and ships, etc. They were formed from various plant fibers, including flax fibers, and their lengths varied.

3.7 Saws

The saw was one of the principal tools in carpentry kits in ancient Egypt. During the pre-dynastic period, saws that looked like knives had been developed to have fine serrated cutting edges and were made of flint (**Figure 2k**). As early as the dynastic period, metal saws were made of copper and used to convert timber into planks. The cut made with these saw knives was very crude.

A pull saw (**Figure 2l**), made of a large forged sheet of bronze with the cutting edge of the teeth set toward the handle, was used in ancient Egypt not very long after the 1st dynasty. The pull saw emerged after problems were experienced in sawing logs into planks by the basic design, taken from the copper knife saws. Most of the large workshop scenes illustrated in tombs show carpenters using pull saws.

With the copper pull saw, it became possible not only to convert timber into good-quality boards but also to cut these to various lengths across the grain and to form sophisticated joints in them [1, 8, 9].

3.8 Scribing and marking tools

These tools are used to score lines and shapes on the surfaces of wood, allowing carpenters to work, cut, engrave them recessed or raised, or saw the wood to the marks.

- The marking knife (**Figure 2m**) was commonly used in ancient Egypt. Most of these tools were manufactured with a smooth wooden handle and a fine bronze blade that is easily inserted into the wood [8].

- The scribal palette (**Figure 2n**), the main tool of an Egyptian scribe, contained two inkwells and a slot to hold reed pens, and dried ink cakes in the ink wells contained black and red ink. It was used to score (mark) lines on wood. Such lines can be seen on the boards of corn mummies' coffins dating back to the Ptolemaic period.

3.9 Sharpening stone and oil flask

Carpentry tools need to be sharpened at regular intervals, as they quickly become dull due to frequent use. Therefore, carpentry tools mainly contain a sharpening stone (**Figure 2o**). In ancient Egypt, the sharpening stone was made of slate, which is characterized by its greenish-gray color, and was located on one of its edges, a hole through which it could be hung on the wall [8].

Lubrication during the process of sharpening the blades of carpentry tools on a sharpening stone was carried out by using a little oil on the sharpening stone. Hence, containers for storing oil were one of the most suitable methods for this purpose. One of the oil storage containers dating back to the New Kingdom (**Figure 2p**) was made from the empty horns of some animals. It was equipped with a wooden stopper at the end, while the other side of the wood was shaped into a spout that took the shape of a spoon [8]. It was also sometimes made of hard, non-porous stones, especially alabaster, granite, etc.

3.10 Smoothing stones

Quartz abrasive stones (siliceous sandstone) (**Figure 2q**) were used to finish and smooth the wood. The abrasion process was carried out in the direction of the fibers, where abrasion of wood in a direction that intersects with the fibers leads to damage to the wood. This process is illustrated by a view in the tomb of *Ti*, 5th dynasty, at Saqqara. It seems that a small amount of abrasive sand with a fine grit was added, in addition to some other liquids such as water or oil, to facilitate this process.

3.11 Wooden mallet

A wooden mallet (**Figure 2r**) was a primitive woodworking tool in ancient Egypt. Many of the found mallets are in bad condition due to daily use in masonry and carpentry work during the Pharaonic period [1, 8–10]. Mallets are made of one piece of wood, often native solid and heavy wood such as Nile acacia; the head is shaped with an adze into a domed form, and the handle is reduced to an elliptical shape.

Wooden mallets, which the carpenters and the masons used, were occasionally found with chisels, awls, and engraving tools in ancient Egyptian times [8]. The mallet was employed for many purposes, such as striking wooden nails in the holes

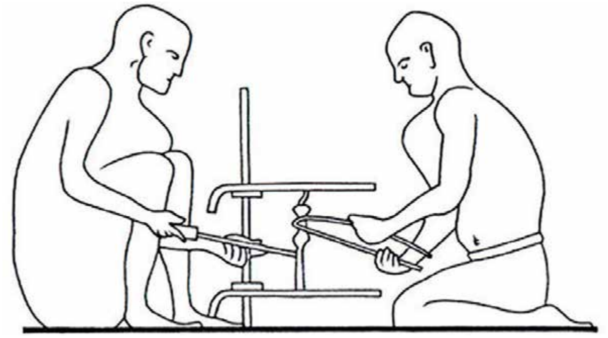

Figure 3.
Scene of turning wood, Petosiris*'s tomb, Ptolemaic period, at Tuna al-Jab.*

and inserting tenons inside mortises, which have been used to join the wooden boards together, in addition to striking firmer and mortise chisels during statuary, boatbuilding, and engraving the mortises for joining wooden planks.

3.12 Lathe

A lathe is a device that rotates a work piece of wood about an axis of rotation to execute a variety of operations such as cutting, sanding, knurling, drilling, deformation, facing, threading, and turning with tools that are applied to the work piece to create an object with symmetry about that axis.

The first depiction of two carpenters working on a lathe was found in the well-known *Petosiris*'s tomb, Ptolemaic period, in Tuna al-Jabal, dating some 300 B.C. (**Figure 3**). The scene shows the turner man sitting on the ground in front of the lathe. He wraps a long rope around the right side of the work piece of wood between the jaws of the lathe and moves the rope with his hands forward and backward, so the piece of wood rotates around its axis. In the direction of the rope's movement from front to back, another turner confronts the piece of wood with the tool that he holds with both hands, scraping the wood away with that sharp tool. Little by little, the turner man forms the piece of wood into a wonderful artistic element. Egyptian turners used flat-blade scrapers and angled skew chisels [1, 8].

4. Woodworking techniques

Carpentry and joinery techniques are better known in ancient Egypt than anywhere else in the ancient world because of scenes depicting woodworking in tomb paintings, reliefs, and found wooden artifacts, as well as tomb models of Middle Kingdom carpentry workshops showing men working with miniature tools.

4.1 Felling the trees

Several scenes of felling trees in ancient Egypt were depicted on the walls of the tombs during the Pharaonic periods, as seen in the tombs of *Sekhem-Ka-Ra* 4th dynasty at Giza, *Nefer*, and *Kaha* 5th dynasty at Saqqara, *Khnum-Hotep* III 12th dynasty at Beni Hassan, and the tomb of *Ipuy* at Thebes [9, 11].

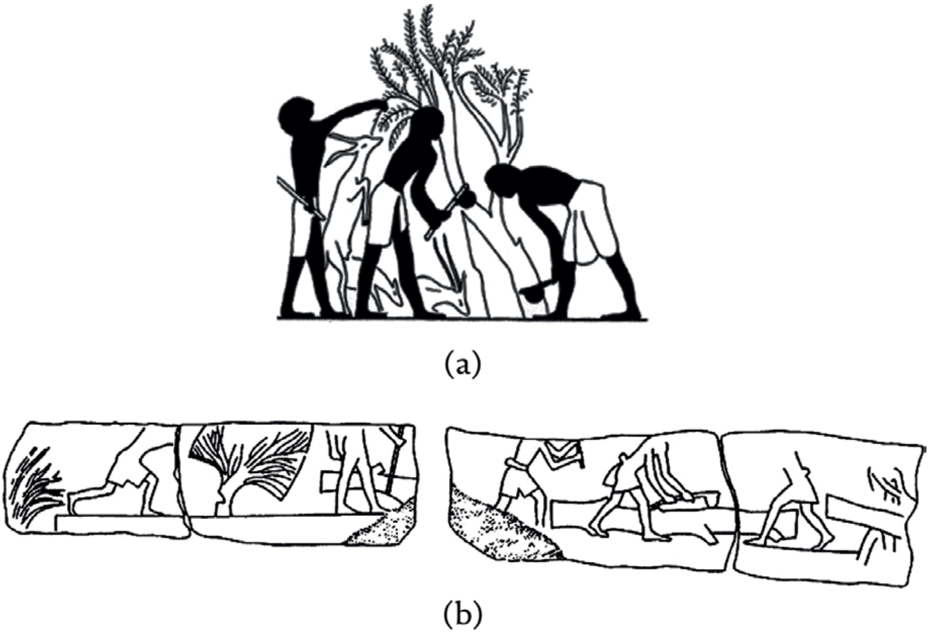

Figure 4.
Scenes of felling trees and chopping the branches by the axes: (a) tomb of Khnum-Hotep *III at Beni-Hassan, 12th dynasty (after Newberry, plate XXIX); (b) tomb of* Sekhem-Ka-Ra *at Giza, 4th dynasty (after Killen, Fig. 15.17).*

The procedure of choosing the right trees was crucial since the timber boards needed to be cut from straight, high-quality trunks that had enough heartwood and fewer faults and were suitable to be fastened to the sawing post. Woodcutters are seen falling trees by employing bronze axe tools with curved cutting edges and incorporating projecting side lugs to slice a deep groove at the base of the trunk. Following the tree's downfall, the branches were removed (**Figure 4**) [11].

4.2 Conversion of logs into planks

After removing the branches, the logs were transported to the courtyard of the carpenter's workshop, where the sawing post was set. The sawing post was set into the ground at the center of the courtyard, to which the log was lashed with a cord. A carpenter would use a pull saw to saw down the green timber into suitable lengths of planks. As the saw cut down the log, the lashings had to be adjusted. Often, a wedge or lever mechanism operated with the aid of a heavyweight; perhaps a stone was pushed into the top of the saw cut. This would help the saw move freely through the green timber. Sawing down timber by these methods is well illustrated throughout the dynastic period (**Figure 5**) [9, 11].

The technique of cleaving was well understood and practiced as early as the predynastic period, as in the case of crudely constructed burial boxes made from irregularly shaped planks that are bound together (e.g., from the pre-dynastic cemetery at Nag el-Deir). Experienced craftsmen could split a trunk of straight grain growth into thin planks with ease, and we can establish that the trunk has been split by following the lines of cleavage that will tend to follow the grain, usually down the tree's rays, through its weaknesses and irregularities. The process of cleavage timber is depicted

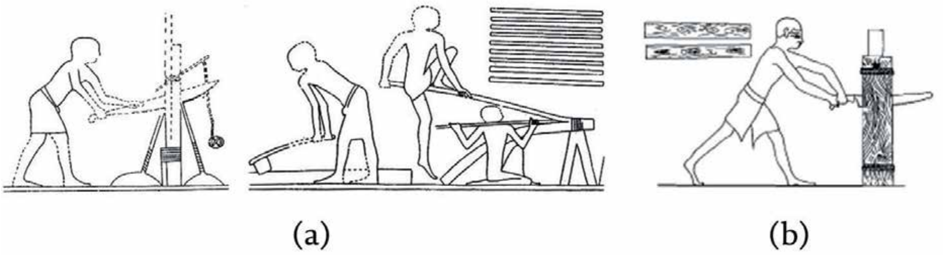

Figure 5.
Scenes of conversion of timber into wood: (a) tomb of Iteti *at Deshasha, 6th dynasty; (b) tomb of* Rekh-Me-Ra *at Thebes, 18th dynasty.*

in the 6th dynasty tomb of *Iteti* at Deshasha. This scene also shows that timber conversion was achieved by a saw, with a log being bound with rope to a vertical sawing post, suggesting that accurately sawing planks would usually not have been greater in length than the height of the sawyer [9, 11].

4.3 Drilling

In the Pharaonic periods, ancient Egyptian carpenters used wooden mallets and chisels, in addition to bow drills, to make various holes and mortises in woodwork. Wood has been drilled for many purposes, the most important of which is preparing wood for joints using wooden pegs, loose tongues, pegs, and various wooden connection elements. The scene in the tomb of *Rekh-Me-Ra* at Thebes, 18th dynasty, depicts a carpenter set on a stone block using a bow drill to drill hole for inserting wooden dowels to connect the frame of the chair to the legs (**Figure 1**).

4.4 Plywood

As early as the 3th dynasty, Egyptian carpenters started laminating thin wood sheets in an effort to create enormous sheets of material that were equally strong and dimensionally stable in all directions. The remnants of a 3th dynasty coffin found in an alabaster sarcophagus in a passageway of the step pyramid at Saqqara serve as an illustration of this early plywood. The coffin's sides, ends, and bottoms (the lid is missing) consist of six layers of plywood, each of which is about 4 mm thick, 4–30 cm wide, and of various lengths. Since none of the wood pieces were long enough for the coffin's length or wide enough for the sides' height, they had to be connected using flat wooden dowels secured in place with tiny wooden pegs to achieve the required dimensions. To give the wood strength and prevent warping, the numerous layers that make up the thickness were also nailed together. The layers were organized with the wood grain alternating in different orientations. The innermost layer featured square (butt) joints, but the outermost layers' edges were beveled at the bottom corners of the coffin, indicating mitred connections [1, 11].

4.5 Bending and turning

The Egyptian carpenters were skilled at bending unseasoned wood in an artificial way. A scene of men damping poles can be seen in the tomb of the 5th dynasty vizier *Ptah-shepses* at Abusir, while a scene in the tomb of Ti at Saqqara (**Figure 6a**) [12]

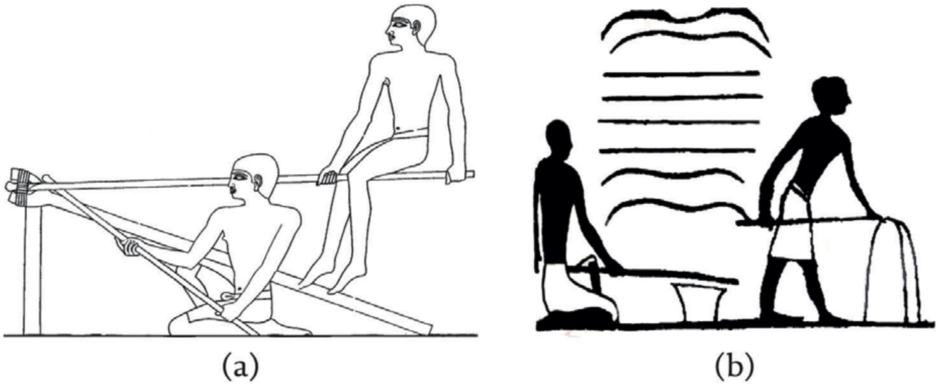

Figure 6.
Bending wood scenes: (a) steam-bending lengths of timber (Wild 1966: Ti*'s tomb, Old Kingdom, Saqqara, plate CLXXIV) and (b) manufacture of bows by steam-bending (Newberry 1893: tomb of* Amenemhat*, Middle Kingdom, Bani Hassan, plate XI).*

depicts the actual bending process: a wooden post is buried in the ground, to which a forked pole with a rope strung across the top of the open fork is attached at an angle; beneath this is the damp pole, which the craftsmen wished to bend. He sat on the end of the pole and pressed its free end downward until the correct shape was formed. He then tied the pole back to the post. To keep the tension maintained until the pole cured and took on its new shape, an additional strut was positioned beneath the bend [9, 11].

In the tomb of *Amenemhat*, the regional governor of the Middle Kingdom, in Beni Hassan, there is a mural (**Figure 6b**) [13] depicting a carpenter steam-bending a piece of wood. By holding the stick over a basin of hot water, he allows the hot vapor to seep into the wood's already saturated cellular structure, softening it. These rods are seen being bent into hoops by another man. The ends of the hoops were buried in the ground to keep the stress on them as they cured and took on shape. This method worked well to create the stack of partially and fully made bows shown above the guy steam-bending. Wheelwrights would have also utilized steam-bending to create pieces for chariots [9, 11].

4.6 Flattening and smoothing

Wood planer tools were not known in ancient Egypt; flattening wood was carried out by the adzes, and other tools, such as abrasive fine-grained sandstones, contributed to shaping, smoothing, and flattening the surfaces of the woodwork, as evidenced by some depictions and the model carpenter's shop from the 11th dynasty found in *Meketra's* tomb.

4.7 Wooden joints

The Egyptian carpenters created remarkable techniques of connecting irregular and small wooden pieces by using interconnecting elements such as dowels, or flat tongues, butterfly cramps, several forms of lashing and pegging, and occasionally in fine woodworks by tongue and groove to overcome the lack of timber suitable for sizable straight planks and to manufacture the desired designs of required wooden artifacts. Though nails were employed to fasten metal to a wooden core as early as the Old Kingdom, they were not used in woodwork until the 18th dynasty [9, 11].

4.7.1 Lashing and pegging

As early as the pre-dynastic period, carpenters used thongs of hide or leather, narrow copper bands, or linen strings to secure the joints of woodwork by lashing or pegging methods. Timbers with holes for lashing were found at Tarkhan; often, this method was used with butt-jointed corners to secure boxes, corners, and coffins [1, 9].

4.7.2 Box and frame corner joints (mitred joints)

Many types of mitred or corner joints (**Figure 7**) were used in ancient Egypt as early as the Old Kingdom, such as half-lap, simple-mitre, shoulder-mitre, double shoulder-mitre, mitre-housing, and dovetailed mitre-housing. Most of these types were usually secured with lashing or pegged with wooden pegs driven diagonally through the connected wooden pieces [11].

4.7.3 Butt joints

Simple butt joints (**Figure 8**) used during the ancient Egyptian periods, pegs, and hide or linen strings have been used to secure these joints. Pre-dynastic burials from Nag el-Deir show some examples of frames or coffins whose corners were connected together by simple butt joints secured by lashing or maybe pegs [11].

4.7.4 Mortise and tenon joints

Mortise and tenon joints are strong and stable; they were well-known in ancient Egypt and common in woodwork as early as the 1st dynasty. There are many variations of this type of joint. The basic mortise and tenon have two components: the mortise hole and the tenon tongue. This joint may be glued, pinned, or wedged to lock

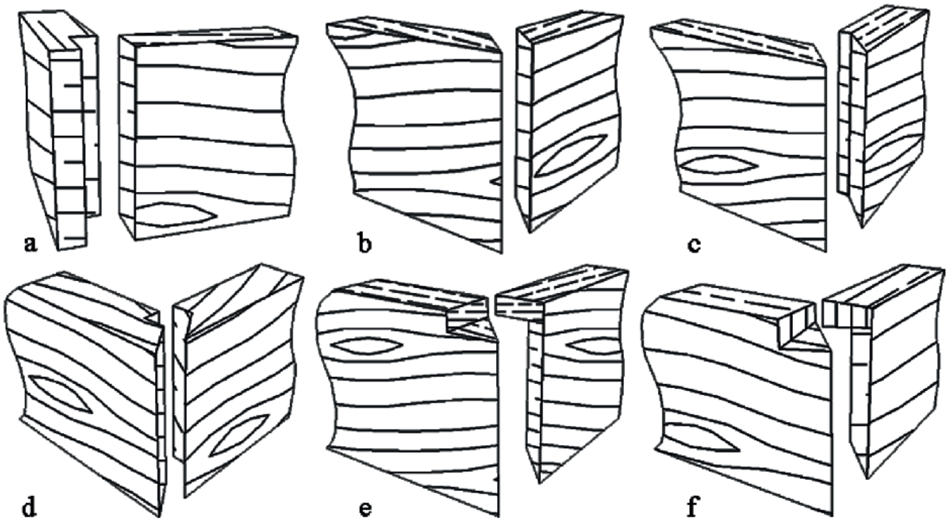

Figure 7.
Frame corner joints: (a) half-lap, (b) simple-mitre, (c) shoulder-mitre, (d) double shoulder-mitre, (e) mitre-housing, (f) dovetailed mitre-housing.

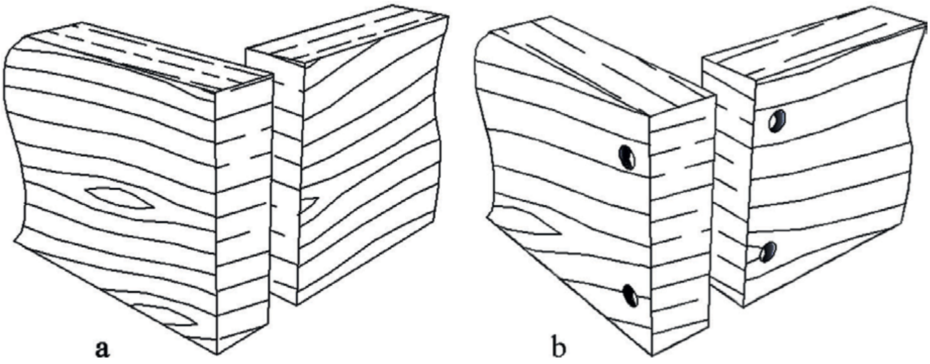

Figure 8.
Frame corner joints: (a) simple butt joints, (b) butt joints with holes.

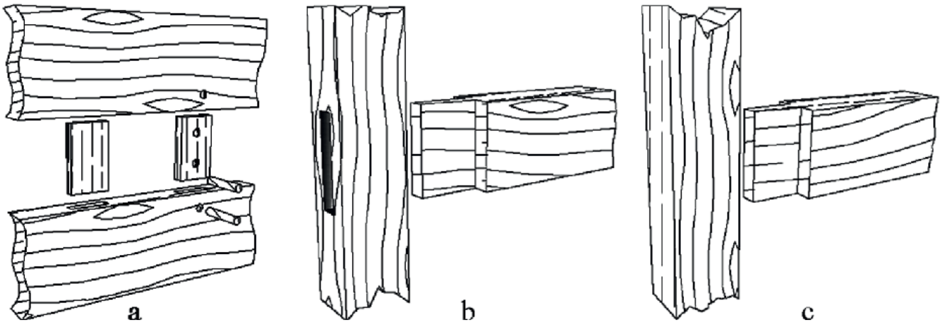

Figure 9.
Mortise and tenon joints: (a) mortise and loose tenon, (b) through mortise and tenon, (c) stub mortise and tenon.

it in place. Mortise and tenon were widely used by the ancient Egyptian carpenters in funerary furniture, boatbuilding, statuary, construction, etc. A variation of this joint technique included:

- Locked (pegged) mortise and tenon joint (**Figure 9a**) that consists of cutting two mortises into the edges of two planks; a separate rectangular tenon is then inserted in the two mortises. The assembly is then locked in place by driving a dowel through one or more holes drilled through the mortise side wall and tenon. This technique is extensively used in boatbuilding, statuary, and coffins.

- Through mortise and tenon (**Figure 9b**), in this joint, the tenon is taken completely through the opposite rail, being visible on the rear side. This joint was widely used in the construction of bed frames as early as the Old Kingdom; for example, the bed frame discovered at Saqqara (Inventory No. 480) and many instances preserved in the Cairo Museum.

- In the stub mortise and tenon joint (**Figure 9c**), the engraved mortise does not go through the work piece, and the tenon is shorter than the thickness of the work piece, so it does not show. This joint was applied to make stools and simple frame constructions. It can be found on the back support frames of chairs. The joint is occasionally secured in place with a dowel passing through the face of the joint and the cheek of the tenon [11]. This joint used in connecting the wooden legs of offering table dates to the Middle Kingdom (GEM-No. 1432) [14].

4.7.5 Dovetailed joints

The dovetail joint is strong because of the way the tails and pins are shaped. The dovetail joint was used in ancient Egypt from the Old Kingdom onward to the Greco-Roman period. For example, the furniture of Queen *Hetepheres*, 4th dynasty, the bed canopy in which the roof poles are dovetailed into the roof beams, and the vertical back pillars and roof beam are joined by barefaced dovetail; the corners of corn mummy coffins recently discovered in Saqqara, dating back to the Ptolemaic period, are connected by dovetail joints. Variations of the dovetail joint that were used in ancient Egypt included:

- The common dovetail joint (**Figure 10a**) was used to fasten the corner boards of boxes and the sides of coffins, for example, the rectangular coffin of the 18th dynasty and the tomb of *Nefer-Khaut* at Asasif, Western Thebes.

- The lapped dovetail joint (**Figure 10b**) was used in drawers; for example, the drawer in the front of *Kemni*'s box, 12th dynasty [11].

4.7.6 Bridle joint

The bridle joint (**Figure 11**) is similar to the mortise and tenon joint; the distinguishing feature is that the mortise and tenon are cut to the full width of the tenon timber. Some examples of using this joint can be seen in the fragment discovered by Emery in 1954 at Saqqara and the try square dating to the Ptolemaic period in the Petrie museum [11].

4.7.7 Scarf joints

A scarf joint is used to get the required extension to the wood planks. The Egyptian timber is relatively short, besides, techniques of cutting timber by saw post produced relatively short planks. The carpenters usually use the scarf joints to manufacture long rails of wood, generally, used in boatbuilding. The variation of scarf joints included [11]:

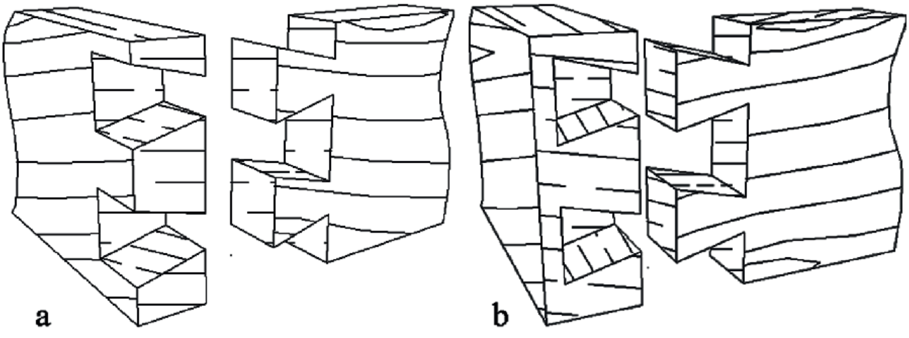

Figure 10.
Dovetail joints: (a) common dovetail joint, (b) lapped dovetail joint.

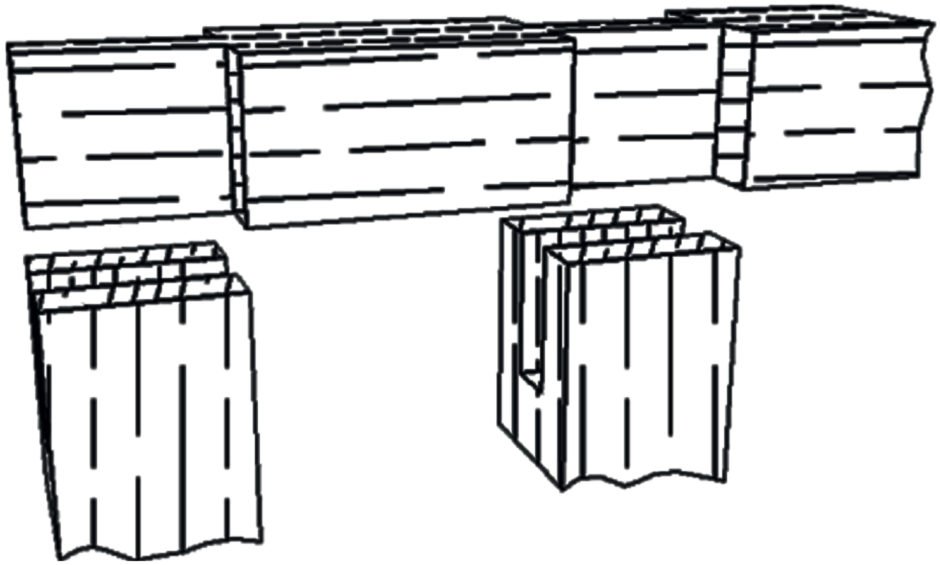

Figure 11.
Bridle joint.

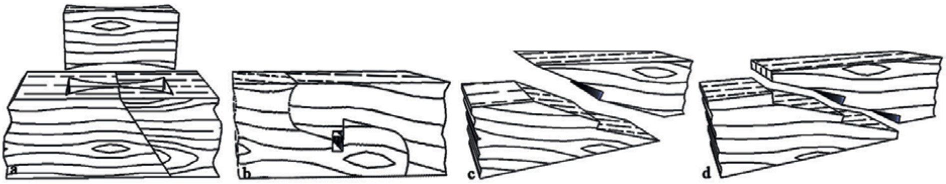

Figure 12.
Scarf joints: (a) common scarf with butterfly cramp locking piece, (b) tied hooked scarf joint, (c) spliced scarf joint, and (d) spliced scarf with shoulder.

- Common scarf with butterfly cramp locking piece (**Figure 12a**).
- Tied hooked scarf joint (**Figure 12b**).
- Spliced scarf joint (**Figure 12c**) (used in Tutankhamun's stick GEM-No. 11442).
- Spliced scarf with shoulder (**Figure 12d**).

4.7.8 Butterfly joint

A butterfly joint secured with dowels, also called a bow tie or dovetail key (**Figure 13**), is a type of joint used to hold two pieces of wood together. A butterfly key resembles two dovetails connected at the narrow part. A negative of the hole is cut out of the board the butterfly will be placed in, and the butterfly is then fitted, keeping the joint together. The assembly is then locked in place by driving two dowels through two holes drilled through the two dovetail side walls and the connected boards. For example, the head area of the coffin of *Wiai* (the craftsmen's chief of the temple of *Amun*), New Kingdom, Saqqara, is connected by that joint.

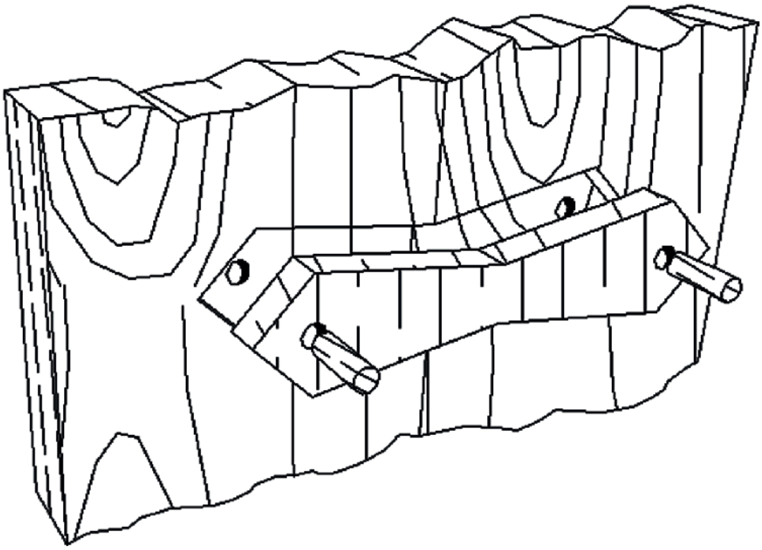

Figure 13.
Butterfly joint.

4.8 Reuse and repair wooden artifacts

During tough economic times, wood becomes even more valuable because it is relatively scarce. Its value is shown not just in the clever construction, woodworking techniques used to create wooden artifacts, and the presence of numerous pieces that show clear evidence of reuse from earlier objects, but also in the reuse of timber fragments and the development of repair methods to deal with challenges like diseased or damaged wood, potential weaknesses such as knots, and gaps between poorly fitting wood sections [6, 15].

In order to repair wood defects (natural or manufacturing defects), the ancient Egyptian carpenters used several methods, including:

- Patching with another piece of wood.
- Drilling out knot holes and filling them with plugs.
- Packing twists of linen into spaces between planks.
- Pastes of calcium carbonate and calcium sulfate were used to build up some missing parts of the wooden artifacts.
- Fill knots and holes, and seal ill joints and gaps between planks with calcium carbonate [4].

For example, the bases of old kingdom human statues in Saqqara (registration Nos. 433, 20859, and 20860) show several mortises, the use of pastes, and small pieces of wood to patch missing parts.

Some of Tutankhamun's black shrines show examples of reused wooden pieces from earlier objects and several repair methods. For example, the inside surface of the roof and cornice of the shrine (GEM No. 21072) is full of old mortises, as well as the remains of painted drawings indicating the reuse of these parts from earlier objects. Some repair methods, such as patching with another piece of wood secured with dowels and white paste, knot holes filled with wooden plugs, and filling gaps and wood voids with white paste, could be seen in shrines (GEM Nos. 21060, 21061, 21062, and 21070) [6].

5. Decorating wooden artifacts

5.1 Glue

In ancient Egypt, glue was not extensively utilized until the 5th dynasty (2494–2345 B.C.). The fine scene in the passage, the south wall of the tomb of *Rekh-Me-Ra*, 18th dynasty, at Thebes, illustrates a worker applying glue to a wooden board with a brush, while in the background, a scene shows a pot of glue being put on a fire to heat glue [1, 11].

To create glue, animal skins and bones would have been boiled in water, allowed to evaporate to concentrate the solution, then poured into ingots and left to solidify. After that, the ingots would either be broken up into smaller pieces or crushed into a powder and if necessary, they would be heated over a fire in a pot with a little water until the glue had thickened again. After that, a brush would have been used to apply it to the inlay and furniture joints [1, 11].

5.2 Painting materials

In ancient Egypt, especially during the Pharaonic era, earthen oxides were the primary source of paint materials. The Egyptian artisan used both gypsum ($CaSO_4{\cdot}2H_2O$) and calcium carbonate ($CaCO_3$), or so-called gesso (a mixture of whiting material and glue, gum, or egg yolk), as multifunction materials. For example, gesso was used as a smooth ground layer if paint was to be applied or to cover poor-quality wood; a white pigment, patching the natural defects in timber; to hold inlay materials in place; and as a base or adhesive to apply gold or silver sheet upon it.

Natural oxides were commonly used as painting materials in ancient Egypt. For example, hematite (αFe_2O_3) was used for red, azurite $Cu_3(CO_3)_2(OH)_2$ for blue, goethite ($\alpha FeO{\cdot}OH$), orpiment (As_2S_3), and jarosite $KFe_3(SO_4)_2(OH)_6$ for yellow, malachite $Cu_2CO_3(OH)_2$, chrysocolla ($CuSiO_3{\cdot}2H_2O$) for green, carbon black (C) for black and calcium carbonate ($CaCO_3$), gypsum $CaSO_4{\cdot}2H_2O$, and huntite ($Mg_3Ca(CO_3)_4$) for white and preparatory layer. Analysis of the mural paintings, cartonnage, wooden artifacts, funerary artifacts, and papyri demonstrates that the ancient Egyptians also produced synthetic frit pigments, such as Egyptian green $(CaCu)Si_4O_{10}$ and Egyptian blue [16].

5.3 Gilding and plating

Gold layers were used, along with precious metals for decorating and plating the wood surfaces. The gilding wood technique is one of the extensive methods used in decorating the wood from dynastic period onward the Greco-Roman period. This gilded wood would cover important relics like statues, furniture, coffins, chariots, sticks, etc. [1, 11, 17, 18].

5.4 Leather

Basically, leather thongs were used for lashing and securing the wooden joints and furniture elements, as well some tools consisted of two pieces such as adzes and axes [11]. Leather is also used in some stools as a protective covering and decorative element.

5.5 Varnish

Generally, two types of varnishes were used in ancient Egypt, translucent or colorless varnishes, though now yellow, brown, or red, that were utilized for covering the painted layer on wooden artifacts such as coffins, stelae, statues, and other objects. The black varnish (Black resin) has a religious and ritual background, this resin is often made of a combination of plant oil, animal fat, tree resin, beeswax, and bitumen—which is solid crude oil, usually used to cover the funerary furniture, statues, coffins, etc. [1, 11].

5.6 Inlay

The ancient artisan used many types of materials as inlay, such as ivory, glass, painted pastes, precious stones, and wood, one of the most common inlay woods is African black wood [1, 11].

5.7 Bark

The Egyptians extensively used the bark, particularly during the 18th dynasty, for decorating wooden artifacts, such as chariots, bows, walking sticks, and other objects from Tutankhamun tomb, 18th dynasty, Thebes. Perhaps they decorated the wood with the bark of birch trees from Anatolia or North Persia and cherry trees from Persia and the Caucasus [1].

6. Conclusion

This chapter demonstrated that although the Egyptians knew carpentry and joinery at least since the pre-dynastic era, they had attained a high level of skill by the time of the Old Kingdom, as shown in the scene of a carpentry workshop depicted on the walls of *Ti*'s tomb, 5th dynasty.

Although Egyptian carpenters widely used some types of native trees (Acacia sp., sycomore fig, Tamarisk sp., etc.) in funerary furniture, they realized that most indigenous trees produce either small or poor wood. Because of the development of tools and carpentry skills, besides the increased need for high-quality wood, ancient artisans realized the necessity of importing high-quality wood from neighboring countries, for example, cedar, juniper, ebony, etc.

Techniques of woodworking in ancient Egypt included drilling, bending, plywood, turning, flattening, and smoothing. In addition, the Egyptian carpenters developed many wood joints, such as corner joints, butt joints, mortise and tenon joints, dovetail joints, scarf joints, etc., and several methods of fittings and fixtures, such as nails and tacks, hinges, brackets, and locks.

The stress of economic conditions and the scarcity of wood are the major motives for developing methods of repairing natural or manufacturing defects in wooden artifacts, in addition to the reuse of wood fragments from earlier objects.

Decorating techniques in ancient Egypt showed high skills in using natural and synthetic painting materials, leather, bark, inlay materials, gilding, and varnishes to adorn daily life and funerary wooden artifacts.

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Chapter 2

Using Machine Learning to Improve Fire Safety of Timber Structures

Nida Ishtiaq, Thomas W. Loh and Kate T.Q. Nguyen

Abstract

Fire safety and fire resistance studies are a vital part of construction. Most conventional fire safety analyses require a combination of computational and experimental methods, making them time-consuming, technically challenging, and financially expensive. By comparison, artificial intelligence-based methods can be computationally more straightforward and more time-efficient, with the added benefit of performing simulation-based tests. This paper focuses on the use of machine learning methods to enhance the understanding and analysis of timber structures in fire. Important works in the field of fire safety and fire resistance for timber structures using artificial intelligence methods are reviewed. The works presented emphasize the importance and accuracy of artificial intelligence and machine learning-based methods in this field.

Keywords: timber structures, fire safety, fire resistance, artificial intelligence, machine learning

1. Introduction

Timber is increasingly used as a construction material, with some structures being predominantly timber and others a hybrid of timber, steel and/or concrete. In residential construction, up to triple-story timber structures are common. Meanwhile, in taller construction, timber is being used increasingly due largely to the rapid growth of the mass timber construction (MTC) sector. For example, the 25-story Ascent building in Milwaukee, Wisconsin, was crowned as the world's tallest timber-concrete hybrid structure by the Council on Tall Buildings and Urban Habitat (CTBUH) in 2022 (**Figure 1**) [1]. The building's height is 86.6 meters (284 feet), which made it the tallest building in two categories: the world's tallest timber building (previously held by an 85.4-meter-high building in Norway); and the tallest concrete-timber hybrid building (previously held by an 84 meters high building in Austria). The revival and growing popularity of timber (including engineered timber products) as a construction material is being driven predominantly by its potential to reduce greenhouse gas emissions from the global construction industry to deliver a net-zero built environment. Timber is also increasingly considered for its' high specific mechanical

Figure 1.
Photograph of the ascent MKE building under construction revealing the extensive use of mass timber products in the supporting structure [2].

properties, favorable acoustic and thermal insulation properties, and a high degree of prefabrication, leading to lower construction costs.

Along with cost and sustainability, fire safety is an essential part of construction and building design, and this is particularly true for timber structures due to their inherent combustibility. Standards and tests are available to help assess building fire safety; however, they are typically complicated, time-consuming, and expensive. There is growing interest in the adoption of machine learning to assess building fire safety. In a broad sense, a machine learning system is trained for a set of data, which helps the system learn about the data's characteristics. The learned system can then be applied to identify faults, characteristics, or classifications from similar datasets. For fire safety, this could include important fire safety considerations such as fire prevention, spread, and the response or performance of the building material during fire.

Machine learning has found use in many applications, including object identification and classification, fault detection, and automated tracking systems. However, the use of machine learning in fire engineering is limited [3], with most research relying on traditional methods to assess fire safety. This can lead to an inefficient use of resources [4]. There has been some development in the use of machine learning-based techniques for various aspects of fire engineering, including fire safety and fire resistance [5–8]. However, the existing work has been largely confined to steel, concrete, and other composites [9, 10]. Many studies report machine learning as an accurate method for assessing fire properties and behavior of construction materials. Examples of the application of machine learning to construction materials exposed to fire are presented in **Figure 2**.

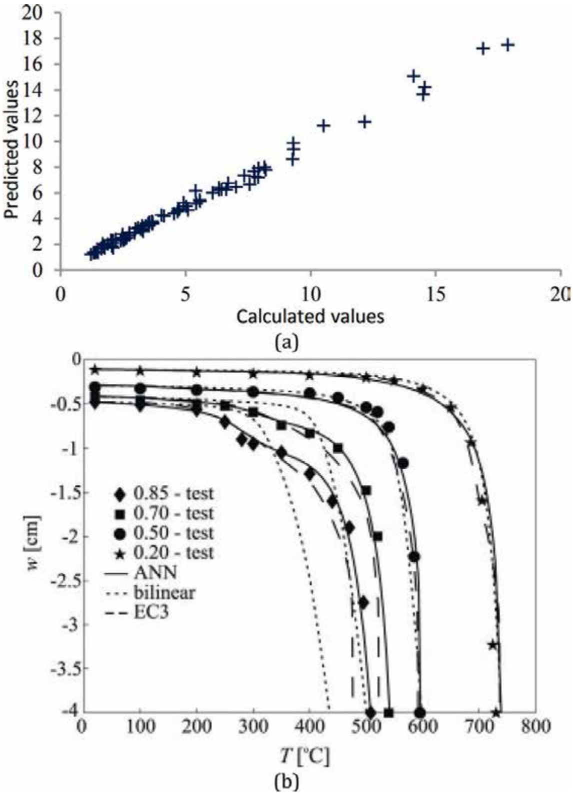


Figure 2.
Examples of applications of machine learning methods to assess fire performance constriction materials. (a) Fire resistance for reinforced concrete columns under eccentric compression loading and exposed to fire. (b) Deflection behavior of structural steel beam subjected to a midspan concentrated load and uniform heating [11].

Lazarevska et al. [11] applied artificial neural networks (ANN) to evaluate the fire resistance of reinforced concrete columns under simultaneous eccentric compression load and fire exposure. For example, the mean absolute error of the predicted from measured fire resistance was 0.23. As another example, Hozjan et al. [12] used ANN to formulate the elevated temperature material model to analyze structural steel frames during fire. The ANN model was reported to be in good agreement with experimental findings and of higher accuracy than a standard bilinear material model.

This chapter discusses notable machine learning studies that consider fire safety analysis of timber as a construction material, with emphasis on the importance and viability of machine learning methods in this field. In the following sections, a brief description of machine learning is presented, followed by a selective review of notable research concerning the fire safety and fire resistance assessment of timber structures using machine learning and artificial intelligence (AI) methods.

2. Machine learning

Machine learning differs from traditional optimization and computational algorithms because it uses a dataset to build a model that describes a key feature or property for a problem or scenario. For example, the fire behavior of a building façade

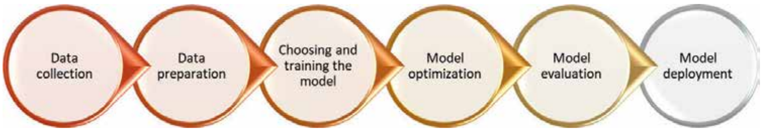


Figure 3.
Process flow for the basic machine learning developmental process.

material [13, 14]. The dataset can be self-generated or gathered from external sources. Once the dataset is established, it is divided into training and testing data. The training data is used to train the machine learning algorithm to build the model for the feature or property of interest for the problem being solved. The trained model can then be tested (using the testing portion of the dataset) to evaluate the accuracy and efficiency of the model. The basic machine learning development process is represented schematically in **Figure 3**. The datasets required by machine learning methods are often large, particularly for training. The size of the dataset needed to develop an accurate model is dependent on the application, the type of algorithm used, and the feature/property considered. Machine learning models can require significant investment (financial and time) to establish the training dataset; however, the trained models are typically much faster than traditional computational algorithms.

There are many types of machine learning algorithms. The fundamental machine learning algorithm is the ANN [15], which is inspired by the design and structure of neuronal networks in the human brain. There are many variant designs to the ANN. For example, recurrent neural networks (RNN) for processing sequential or time series data [16], or convolutional neural networks (CNN) for processing structured data arrays such as images [17]. Many other algorithms and methods have been developed for machine learning, which can be divided into various classes or paradigms, such as supervised learning, unsupervised learning, instance-based learning, reinforcement learning, and ensemble learning. Supervised learning algorithms (e.g., Naïve Bayes [18], decision tree [19]) learn a function to map input data to output data; unsupervised learning algorithms (e.g., K-means clustering [20]) are fed data to identify features or patterns based on this data without any specific instructions or labels for the data; instance-based learning algorithms (e.g., K-nearest neighbors [21]) learn from specific 'instances' in the data to make predictions based on the similarities between the new and training data; reinforcement learning algorithms (e.g., Q-learning [22], Monte Carlo tree search [23]) learn to make decisions by interacting with the environment; and ensemble learning algorithms (e.g., bootstrap aggregating (also known as Bagging) [24], random forest [25]) combine predictions of multiple models with improving overall performance and generalization.

3. Machine learning for fire safety of timber

This section discusses prominent studies in the field of fire safety engineering that use machine learning for timber structures. The methods developed by various authors are briefly explained, and the results of the proposed methods are presented.

3.1 Evaluation of the combustibility of timber

The influence of guided flame on the combustibility of various timber species was investigated using AI-based methods by Olimat et al. [26]. The work discussed the importance of using AI for the combustion industry, specifically for the ignitability and combustibility of wood products. The current best techniques used in combustion science (computational fluid dynamics, CFD), are known to have issues handling the extensive datasets associated with combustion. Machine learning and AI on the other hand typically require large amounts of data to function efficiently and accurately. For these reasons, they appear to be an excellent fit for carrying out combustibility analyses.

Olimate et al. considered four types of timber species. Two soft woods (white pine, *Pinus strobus*; and khasya pine, *Pinus kesiya*), and two hard woods (white oak, *Quecus alba*; and beech, *Faqus sylvatica*). The physical model for the timber in the conducted experiments is represented schematically in **Figure 4**. Where, $\dot{Q}_{Ext}$ is the external incident heat flux, $\dot{Q}_{Cond}$ represents the deep conduction heat transfer, $\dot{Q}_{Char}$ represents the char energy transfer by conduction into the prolysis layer, $\dot{Q}_{Conv}$ is the convective heat transfer through any cracks in the specimen, and $\dot{Q}_{Loss}$ is the sum of convective heat transfer loss and radiation heat transfer loss.

The experiments were conducted to collect data, which was then modeled using an ANN algorithm. This model was used to predict the smoke characteristics of the various types of wood. Performance analysis was conducted using statistical analysis to examine the model's prediction capacity. Specifically, the mean square error (MSE) and coefficient of determination (R^2) were calculated to determine the difference between anticipated and experimental values. After the selection of appropriate values for MSE and R^2, the closeness of the experimentally measured and numerically determined results was considered, **Figure 5**. Further results studied various burning indicators including the expected burning rate, charring rate, specific smoke extinction area, and extinction coefficient for the wood species exposed to incident heat flux values of 25 and 50 kW/m^2. The good agreement between the measured and ANN-predicted values highlighted the high accuracy and usability of AI methods in comparison to experiments that may not be feasible or easy to conduct using traditional methods, especially for complex cases.

3.2 Determination of timber temperature during fire

Nikoo et al. [27] present an investigation into the temperature of rectangular timber cross-sections exposed to fire. The study performed a structural analysis of a timber structure exposed to fire and considered the distribution of temperature in the cross-section of the timber after a certain period, typically 30 or 60 minutes. The ANN algorithm used in this study was based on the echolocation capabilities of bats

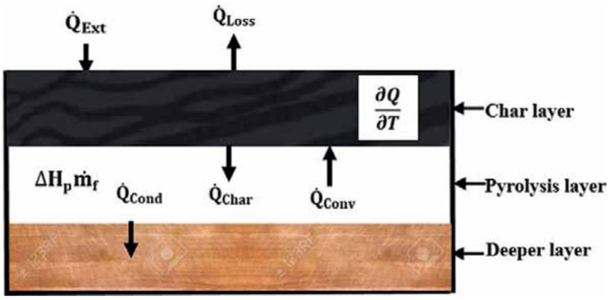


Figure 4.
Schematic representation of the physical model for experiments [26].

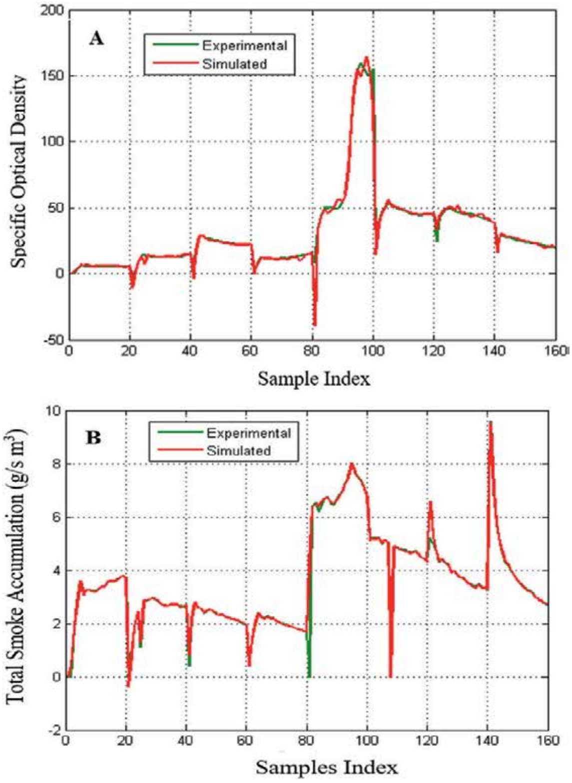


Figure 5.
Comparison of experimental and simulated results. The specific optical density is shown on the left, while the total smoke accumulation is shown on the right [26].

and is fittingly known as the bat algorithm (BA) [28]. The dataset was constructed by recording the timber temperature in 5-minutes increments using the software package SAFIR [29]. The analysis considered different cross-sectional sizes and timber densities. The total cycle was 60 minutes. The resulting dataset consisted of 54,776 samples of timber with varying characteristics. 70% of the samples were used for training, and the remaining 30% were used for testing. The size of the cross-section, the coordinates of the point of measurement, the time of fire exposure, and the timber density were used as input parameters to the ANN algorithm. The temperatures within a timber cross-section were calculated using feed-forward ANN models.

The ANN algorithm showed a high level of accuracy and a low error rate during training; however, the performance was not shown appropriately in the testing phase. The genetic algorithms and bat algorithms were then used to adjust the weights and biases in the network to reduce the error rate. A total of six models were carried out, where three models were developed using the BA and three were developed using the genetic algorithms (GAs). The models were compared using average absolute error (AAE), mean absolute error, correlation coefficient, and straight-line slope indicators. The statistical indices of each model are shown in **Table 1** [27]. The results demonstrated good performance for all six ANN models. The BA-ANN2L(6-4) was the best-performing method due to its higher flexibility and accuracy as compared with other models. The high level of performance demonstrates the potential for machine learning methods to predict the thermal response of timber structures during fire.

Model	All dataset			
	MAE	AAE	R^2	y = ax + b
GA-ANN 2 L(7–6)	8.96	0.058	0.9985	y = 0.9984x + 0.6274
GA-ANN 2 L(7–3)	8.19	0.049	0.9988	y = 0.9987x + 0.5045
GA-ANN 2 L(6–5)	7.42	0.074	0.9990	y = 0.999x + 0.3993
BA-ANN 2 L(7–6)	7.32	0.064	0.9990	y = 0.999x + 0.3835
BA-ANN 2 L(7–5)	6.73	0.040	0.9991	y = 0.9981x + 0.8528
BA-ANN 2 L(6–4)	6.22	0.035	0.9992	y = 0.9992x + 0.2427

Table 1.
Statistical analysis of different models in the dataset [27].

3.3 Evaluation of timber fire resistance

One of the earliest works to consider the fire safety of timber through machine learning methods was conducted by Naser [30]. AI models were used to evaluate the fire resistance and performance of timber structures at the material and element levels. When examining the material level performance, various timber properties such as thermal, mechanical and temperature-dependent properties were collected and the effect of high temperature on these properties was studied through derivation of universal material models. At the element level, the AI-based models and expressions were derived to evaluate the response of various timber members such as floor assemblies, timber beams, columns, and two types of timber connections under elevated temperature.

The developed AI models were in fact hybrid models using ANN with symbolic regression (SR) and genetic algorithms (GAs). The database used for training and testing was collected from published fire tests in the open literature. 70% of the compiled database was used for training of the AI models, while the remaining 30% of the data was used for testing. The prepared databases were fed into the ANN tool in MATLAB for analysis, followed by processing through GAs. Variables best describing any given phenomenon/property were encoded with terminal codes using candidate solutions (which utilized symbolic regression to describe the unique relations between input and output parameters). The performance of the generated AI models was tested against existing methods for various timber properties/parameters including thermal conductivity, specific heat, density, Young's modulus (in tension), compression strength, tension strength, shear strength, and charring depth.

The analysis considered timber flooring assemblies, beams, columns, and connections (nailed and finger-jointed). The study demonstrated that the proposed AI methods were capable of sufficiently capturing the thermal and structural response of most of the timber elements and components involved in the study. Select results are presented in **Figures 6–9**. The AI-predicted temperature-dependent thermal conductivity for wood is shown in **Figure 6**, while the charring depth resulting from pyrolysis is shown in **Figure 7**. The predicted temperature rise on the unexposed surface of timber flooring assemblies is shown in **Figure 8**, and the fire resistance is presented in **Figure 9**. A full summary of all results including other properties and structural components are reported in [30]. Despite the encouraging results, the authors conclude that further development of fire testing databases was necessary to further develop efficiency and accuracy of analyses using AI models. It was further concluded that

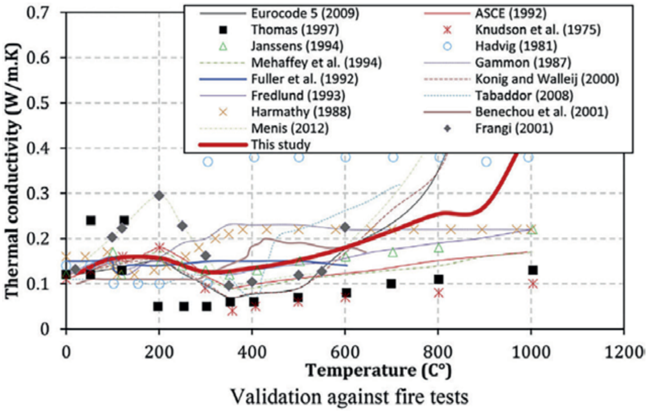


Figure 6.
The AI-derived expressions for thermal conductivity (red curve) compared to experimentally measured values from fire tests [30].

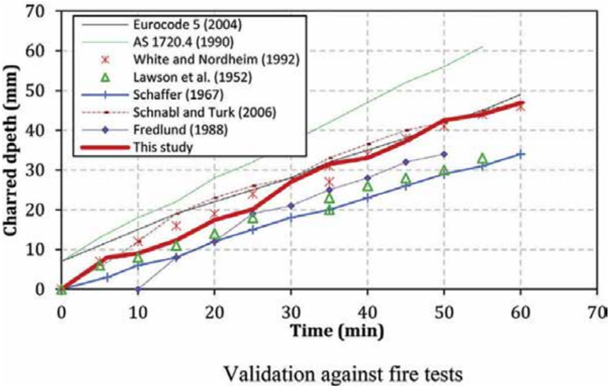


Figure 7.
The AI-derived expressions for charred depth (red curve) compared to experimentally measured values from fire tests [30].

while the AI models worked well, they are still applicable in a more effective manner if used in conjunction with traditional fire resistance evaluation methods.

3.4 Prediction of fire resistance ratings for timber floor structures

As another example, Tung et al. [31] presented a novel method using ANNs to predict the fire resistance ratings of wooden floor structures. The data used for conducting the research was developed by the National Research Council of Canada [32]. Like the performance evaluation conducted by Olimat et al. [26], the performance of the ANN was evaluated through the coefficient of determination and the mean squared error. A total of eleven-floor assembly properties were selected, including applied load (ALD), ceiling finish layer (CFL), and sub-floor type (SFTY). The dataset was randomly divided into three parts, where 80% was used for training, 10% was used for validation, and the remaining 10% for testing. The ANN model used a sigmoidal function for activation and a feed-forward back-propagation learning method. This method uses errors in network output to adjust weights in each layer in two separate

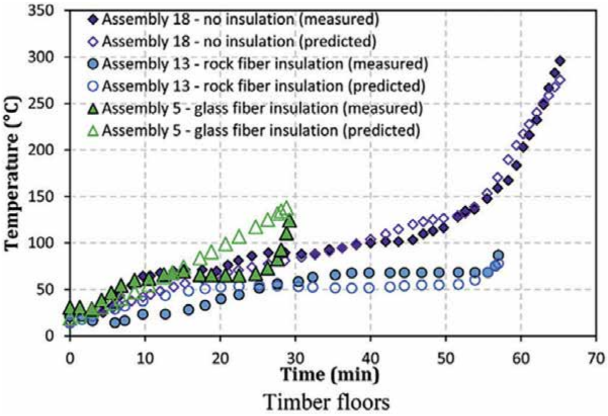


Figure 8.
Cross-checking to validate AI-derived expressions for timber floors (open markers) using structural components that were not part of training data (closed markers) [30].

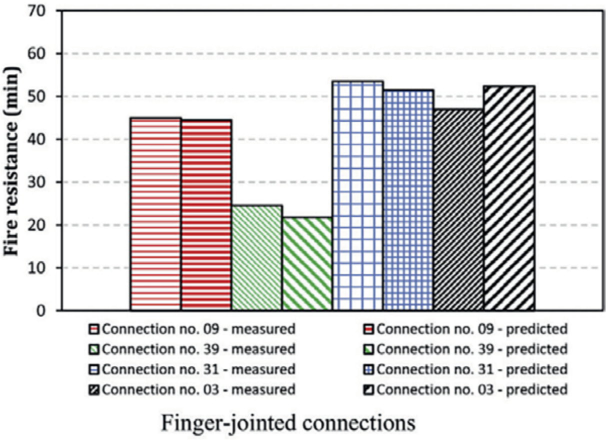


Figure 9.
Cross-checking to validate AI-derived expressions for finger-jointed connections using structural components that were not part of training data [30].

processes, namely the feed-forward and back-propagation processes. A comparison of eight ANN models considered in the study revealed the Levenberg-Marquardt algorithm to perform best in the training, testing, and validation phases with a low number of epochs. Similar comparisons for the variant number of neurons in the hidden layer of the ANN were conducted, which resulted in the selection of six neurons in the hidden layer for the proposed method.

A sensitivity analysis was conducted for the various input parameters on the fire resistance ratings. For each of the eleven-floor assembly parameters the value was changed from low to high in five increments while keeping the other inputs constant, the results are shown in **Figure 10**. The five levels of input variables are shown on the horizontal axis, while the vertical axis represents the fire resistance rating for the corresponding wooden floor assembly. The ANN model revealed the applied load and number of ceiling finish layers to be the most important parameters when considering the fire resistance of timber floor assemblies.

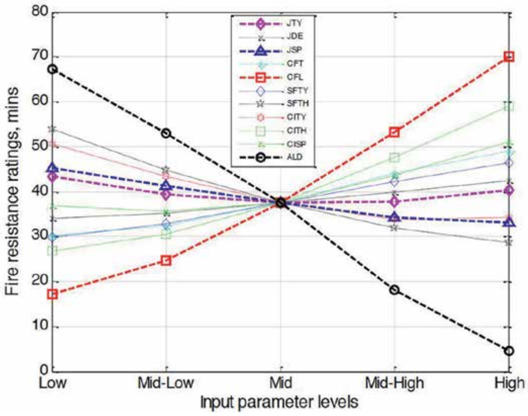


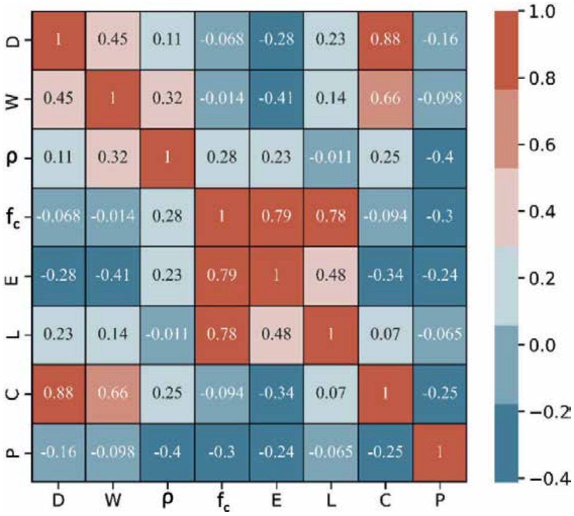
Figure 10.
Fire resistance rating in minutes versus input parameter level [31].

3.5 Evaluation of fire resistance for timber columns

The use of explainable machine learning models to evaluate the fire resistance of glued laminated timber (GLT, glulam) and cross-laminated timber (CLT) columns has been explored by Esteghamati et al. [33]. The authors developed eight explainable models using single- and ensemble-based algorithms, as well as the geometric- and material-related properties of the GLT and CLT timber columns. The machine learning models investigated were multiple linear regression (MLR), support vector machines (SVM), regression trees (RT), adaptive boosting (AdBoost), extreme gradient boosting (XGB), light gradient boosting machines (LGBM), random forest (RF), and k-nearest neighbor (KNN). The models utilized extensive experimental data from various sources to compile a comprehensive database [34–37]. These works considered full-scale timber columns exposed to a cellulose fire from all four sides following standard fire testing methods (ISO 834 [38]). The constructed database considered geometrical properties of the timber columns (cross-sectional depth, D; width, W; and length, L) and material properties (density, ρ; compression strength, f_c; modulus of elasticity, E; load-carrying capacity, C; and load level, P). The database was randomly split into training (70%) and testing (30%) portions. The measured column fire resistance (R) was the output data or response to be predicted. A correlation of the various properties in the compiled database is presented in **Figure 11**, which was obtained according to spearman correlation (ρ_s).

The machine learning model developmental workflow is depicted in **Figure 12**. The workflow includes a threefold cross-validation of the training data via randomized and grid search methods and cross-validation of the testing data through accuracy measures such as the mean absolute error, root mean squared error (RMSE), and the coefficient of determination. A comparative analysis of the two best-performing models of prescriptive fire resistance assessment methods was conducted. Namely, Lie's method [39] and the national design specifications (NDS) method [40].

The selected accuracy measures for the machine learning algorithms are shown in **Table 2**. It was revealed that the RF was the highest-performing algorithm, followed closely by XGB. Therefore, these models were studied further, including an analysis of the important parameters for each algorithm. Capacity was identified as the most important parameter for the RF algorithm. More features contribute to the XGB



	D	W	ρ	f_c	E	L	C	P
D	1	0.45	0.11	-0.068	-0.28	0.23	0.88	-0.16
W	0.45	1	0.32	-0.014	-0.41	0.14	0.66	-0.098
ρ	0.11	0.32	1	0.28	0.23	-0.011	0.25	-0.4
f_c	-0.068	-0.014	0.28	1	0.79	0.78	-0.094	-0.3
E	-0.28	-0.41	0.23	0.79	1	0.48	-0.34	-0.24
L	0.23	0.14	-0.011	0.78	0.48	1	0.07	-0.065
C	0.88	0.66	0.25	-0.094	-0.34	0.07	1	-0.25
P	-0.16	-0.098	-0.4	-0.3	-0.24	-0.065	-0.25	1

Figure 11.
A depiction of spearman correlation structure for the compiled database by Esteghamati et al. [33].

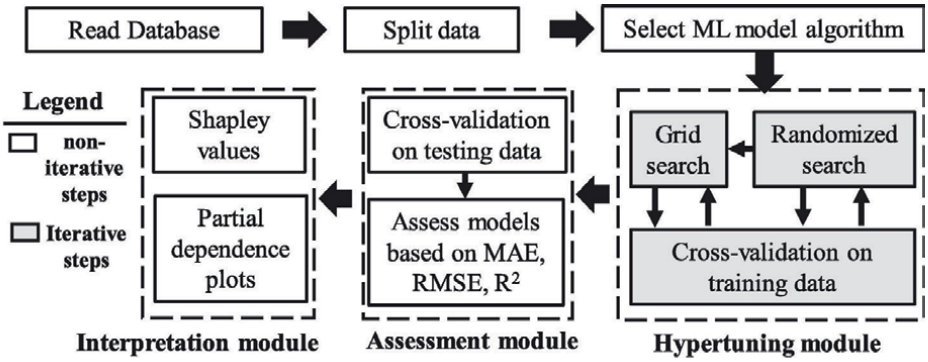


Figure 12.
An overview of the machine learning model development [33].

algorithm, with the highest contribution factor being the capacity, followed by width, modulus of elasticity, and depth. This suggests that loss in capacity due to charring of timber columns is the most important factor in the evaluation of fire resistance for timber columns.

Another interesting comparison presented in [33] is the comparison of the best-performing machine learning models with the prescriptive equations (Lie's method, the NDS) in terms of observed and predicted resistance of timber columns, **Figure 13**. The machine learning algorithms were not given the complete testing data, rather a subset was used for the machine learning algorithms, which was also calculable by the prescriptive methods. The comparative analysis revealed the underperformance of the prescriptive methods. The R^2 metric for both Lie's method and the NDS is quite small, respectively, 0.64 and 0.4, which shows that these methods are incapable of explaining the variability of fire resistance for almost half of the time. The same metric for the RF and XGB shows high confidence with values of 0.9 and 0.89, respectively. Similarly, the RMSE for machine learning methods was also considerably lower

Algorithm	Training			Testing		
	MAE	RMSE	R^2	MAE	RMSE	R^2
MLR	2.19	6.06	0.88	2.20	6.10	0.81
SVM	2.32	6.74	0.85	2.25	6.70	0.77
RT	2.55	9.13	0.73	2.37	7.04	0.75
AdaBoost	2.30	6.58	0.86	2.33	6.51	0.78
XGB	1.95	4.82	0.92	2.24	5.95	0.82
LGBM	2.69	9.87	0.69	2.73	8.91	0.60
RF	1.90	4.87	0.92	2.20	5.55	0.84
KNN	0.50	0.88	1.0	2.30	7.29	0.73

Table 2.
Values of accuracy measures for the implemented machine learning algorithms for training and testing [33].

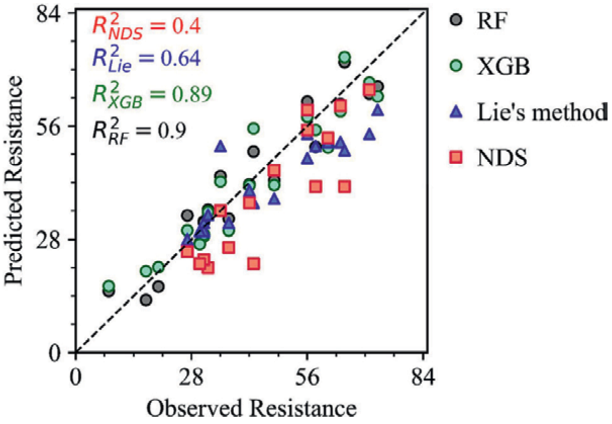


Figure 13.
Comparison of best-performing machine learning methods with prescriptive equations for fire resistance [33].

than the prescriptive methods, 5.05 and 5.95 minutes for RF and XGB, respectively and 8.98 and 11.63 minutes for Lie's method and the NDS, respectively. A similar trend was also reported for the average ratio of predicted-to-observed fire resistance. Importantly, an observed bias in the estimation obtained by prescriptive methods, especially Lie's method, for higher values of fire resistance was also reported. It was concluded that the prescriptive methods underpredict the fire resistance of timber columns, which can lead to overdesign.

4. Challenges and opportunities

The studies presented emphasize the usefulness of machine learning methods for various fire safety engineering principles, analyses, and implementations. However, there are compromises and opportunities associated with the use of these approaches for timber fire safety evaluation. Conventional methods to develop performance-based design require extensive calculations, studies, and experiments to be conducted to reach substantive results [41]. These methods can provide a high level of accuracy;

however, the amount of time and cost needed to develop the solution often outweigh the advantages. Machine learning-based methods are proving to be reasonable alternatives to the conventional methods, encouraged significantly by their ease of implementation [9]. However, they typically require a large amount of data, which is often not readily available without conducting experiments. This can be an important influence on cost-effectiveness and impact their practical implementation in many engineering applications. There is, however, an opportunity in the sharing of data for the creation of high-quality and freely available datasets to promote the fire safety of timber structures, thereby enabling its greater use in buildings and the decarbonization of the global building and construction sector.

5. Conclusions

Fire safety engineering is one of the most important aspects of construction, especially for timber structures. However, the conventional methods for fire safety evaluation require extensive experiments, which sometimes incur huge costs and pose a practical limit on the experiments conducted for a thorough fire safety analysis. In recent times, artificial intelligence (AI) and machine learning (ML) based models have been developed and used for various analyses for many applications, specifically for safety studies. This paper highlights some of the important studies conducted for fire safety engineering of timber structures. These studies feature the potential for AI- and ML-based methods to enable a more thorough and efficient assessment of fire safety in timber structures without the use of expensive or time-consuming complex experiments.

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Chapter 3

Mass Timber and the Disruption of the Building Sector

Azzeddine Oudjehane

Abstract

Over the past decade, the resurgence of engineered wood products, such as cross-laminated timber for buildings, has inspired a change in the way we build. Driven by an effort of the construction sector to become more sustainable and have lower carbon impacts, cross-laminated timber presented an opportunity to try to build better. Mass timber is not just a building material but rather a design-to-build concept that includes the use of large and massive elements and building components from engineered wood, such as cross-laminated timber (CLT). In fact, most, if not all, mass timber buildings are often a combination of wood, steel, and concrete. This chapter will bring forward three distinct learning objectives revolving around: identifying and defining mass timber construction recognizing the current state of the mass timber construction globally defining the disruptive characteristics and best practices for using mass timber products in construction projects.

Keywords: mass timber, CLT (cross-laminated timber), EWP (engineered wood products), off-site construction, DFMA (design for manufacturing and assembly)

1. Introduction

The word mass timber originates from the idea of defining and introducing not just one single building material but rather a family of wood-based materials. The concept started with solid wood panel construction in Europe using primarily CLT, or cross-laminated timber. Hence, mass timber commonly describes a family of engineered wood products that can be manufactured into large solid panels and are known for their strength, durability, versatility, and sustainability. Mass timber can also refer to a building framing system where large-sized and massive engineered wood products are used as structural components. In most applications, mass timber products can be used for beams, columns, floor panels, roof panels, and wall panels. Engineered wood products made for massive and large building structure components are man-made composite materials manufactured by connecting smaller wood elements—such as dimension lumber, veneers, or strands—using adhesives, dowels, nails, screws, or other fasteners. Focused on mass timber made using dimensional lumber at the source of the composite material, this section will:

1. define the various mass timber products, such as cross-laminated timber (CLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), and glue-laminated timber (GLT), often called glulam.

2. describe the various building systems commonly used for mass timber buildings.

Cross-laminated timber (CLT) is a prefabricated engineered wood product consisting of at least three layers of solid-sawn lumber or structural composite lumber. The adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element, as shown in **Figure 1** [2]. The cross-lamination of the lumber laminates is what differentiates the strength of CLT from other mass timber products.

By comparison to traditional building materials such as concrete, CLT is lightweight yet exceptionally strong.

Dowel-laminated timber DLT, unlike CLT, does not use any metal or structural adhesive fasteners between the lumber components of the large mass timber product. It is an all-wood mass timber product made up of lumber boards held together with hardwood dowels. Depending on the building design and for one-way spans, DLT heavy timber can provide more structural efficiency with less volume of materials used than CLT [3].

Nail-laminated timber (NLT) is a mass timber product made by mechanically fastening together with nails the laminations of dimensional lumber aligned on the edge.

The primary and most common use of NLT is in flat roofs and floor-building elements, but it can also be used for walls, elevator shafts, and stair shafts. NLT is also an old engineered wood product made with dimensional lumber aligned on the edge and fastened individually with nails, as shown in **Figure 2**. With applications across construction sectors—commercial, residential, or infrastructure—NLT offers relative ease of fabrication with no specialized manufacturing facility other than a dimensional lumber mill (**Figure 3**).

Glue-laminated timber, or GLT, comprises dimensional lumber bonded with a structural adhesive where the lumber or lamina are staked in only one direction (**Figure 4**).

Unlike cross-laminated timber (CLT) used for floors, walls, and roofs in buildings, Glulam is used for applications such as beams or columns, given its unidirectional strength [5].

Glulam is manufactured using finger-jointed lumber laminated in three or more layers pressed together and bonded with weather-resistant adhesives [6]. Glulam

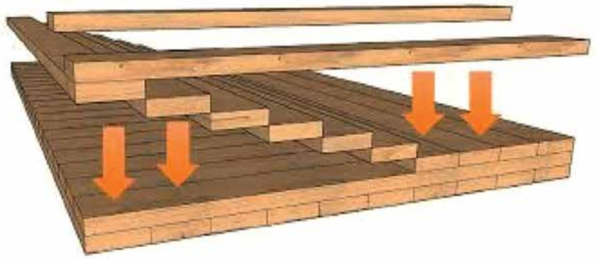

Figure 1.
Cross-lamination of lumber to make CLT [1].

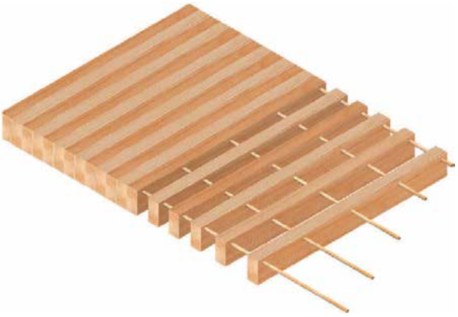

Figure 2.
Assembly of lumber to make (DLT) [4].

Figure 3.
Assembly of lumber to make NLT [4].

can be made straight or curved and arched to customized shapes of design. Glulam is widely used in all types of buildings for load-bearing structural components such as columns and straight or curved beams, as shown in **Figure 5**.

The use of cutting-edge CNC (computer numerical code) machines to manufacture and process mass timber building components has advanced the products to the forefront of innovation. In fact, mass timber products are not commodity products like dimensional wood lumber. The latter has a direct impact on the design and construction management of mass timber projects (**Figure 6**).

Figure 4.
Glue-laminated stack of lumber [4].

Figure 5.
Glulam straight column and curved beams in the atrium of the Trade and Technology Centre at SAIT.

Mass timber building systems commonly used in frame construction can be designed and organized around 3 major configurations to maximize the efficient use of mass timber and construction rendering. The different configurations use various combinations of mass timber products [7].

- Post and beam mass timber system: This design comprises glulam beams and columns creating square or rectangular grids to support mass timber plates (DLT, NLT, or CLT) spanning horizontally. The thickness of the mass timber panels will depend primarily on fire resistance ratings, bracing, and other structural performances. This system is efficient for any type of structure: office buildings, institutional buildings, and tall residential buildings [8].

- Post and plates mass timber system: This type of design, similar to traditional 2-way concrete systems, eliminates the need to use beams and includes glulam posts with CLT plates or floors, as shown below. This type of design, depending on the spacing of the posts and columns, may require much thicker plates and CLT panels, hence limiting the use of other mass timber products. The type of function intended for the building project will drive the adequacy of such systems. The UBC Brock Commons residence has adopted this building system [9].

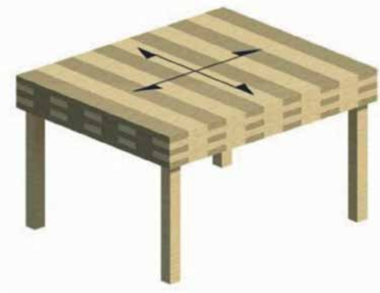

Figure 6.
A two-way post and plate mass timber system [1].

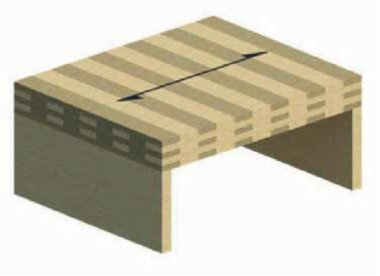

Figure 7.
Load-bearing mass timber system [1].

- Load-bearing mass timber system: This type of design was used in the early attempts to build tall with wood in the UK in 2009 with a 9-story building, "Dalston Lane," and in Australia in 2012 with a 10-story tall wood building "Forte" [10]. The design concept of the honeycomb superstructure is what the buildings use with mass timber walls, plates, and floors comprising the whole structure, as depicted in **Figure 7**.

- Hybrid mass timber systems: In a hybrid system, mass timber elements are combined with either light-frame walls, steel, or concrete components of the superstructure. In fact, all mass timber tall buildings are hybrid systems with the presence of concrete and/or steel components. In fact, the hybrid systems are the most common type of mass timber buildings.

For construction considerations, in addition to building structural design performance of the various mass timber products, architecture features and product availability are still the key decision factors for adopting any of the four mass timber systems [11].

2. State of timber construction

As of March 2024, there were over 1000 mass timber construction projects built or in construction in the US, according to WoodWorks [12, 13]. By contrast, Canada accounted for over 834 mass timber projects, including industrial and some bridges, in accordance with an interactive, up-to-date map by Natural Resources Canada (NRCan) [14]. Although the US WoodWorks accounts for over 1000 mass timber projects currently under design, what is most significant is not so much the total number of projects built or under design but rather the rate of increase in the past decade. Hence, the number of mass timber projects has increased exponentially over the past decade. Europe, on the other hand, is the home to over 70% of the world's mass timber structures taller than 8 stories [15]. In fact, Mass Timber construction started in Europe in the late 1990s with the introduction of solid wood panels such as CLT in Austria with an aim to expand the use of wood in residential construction. Unlike Canada, where residential construction up to 6-story multi-family buildings is predominantly light-frame wood construction, in Austria and across Europe, wood or timber construction is limited to very low-rise buildings, no more than 4 stories in general.

Mass timber started gaining traction in North America after the National Building Code in Canada (NBCC) in 2015 allowed for taller wood buildings up to 6 stories of light-frame construction, then 12 stories in 2020. In the US, the most recent version of the International Building Code—IBC 2021—made allowances to build taller, up to 18 stories high, with limited exposed timber. Most recently, however, in Canada, the province of British Columbia, one of the world's largest exporters of softwood lumber, has proposed code changes to the British Columbia Building and Fire Codes (BC Codes 2024) that would enable taller mass timber buildings, as many as 18 stories [16].

The first challenge for Canada and the US has been making the case for wood and mass timber construction in high-rise or tall buildings for residential construction because up to 6-story buildings are not economically advantageous. Following the changes to NBCC 2015 in Canada with allowance to build up to 6-story tall wood buildings using light-frame construction methods, it was key to demonstrate the feasibility of building taller with wood using mass timber products in order to support proposals to update the building codes [17] and overcome negative perceptions over fire safety around tall wood buildings.

Tall wood buildings have trended in part to demonstrate the constructability, feasibility, and evidence that mass timber could potentially address the challenge for sustainable low-carbon construction. The race to make the case for tall wood buildings, which started in 2009 in the UK, has led to over 40 tall wood building projects between 2014 and 2020, including: Brock Commons in Vancouver, BC, Canada, which in 2017 was the tallest wood building in the world at 18 stories at 58 meters in height [18]; Mjøstårnet in Norway with 18 stories at 85.4 meters in height, also the tallest wood building [4]; and MKE Acsent in Milwaukee, Wisconsin, now the tallest wood building in the world at 285 feet (87 meters) in height for 25 stories [19, 20].

The second challenge for mass timber construction in North America has become a shortage of supply. Growing demand for mass timber buildings, driven by the need to reduce the environmental impacts from the built environment, has resulted in a spike in demand for mass timber products such as CLT, while manufacturing capacity in North America remained limited. As a result, due to a shortage of local mass timber products, projects needed to rely on importing CLT from Europe. Up to 2020, the production of mass timber products such as CLT was concentrated in the Alpine region (Austria, Switzerland, and Germany) before expanding to Nordic Europe. The output volume of CLT production in 2020 in the Alpine countries amounted to 70% of the overall global production of CLT [21]. North America's production only made up 12% of the global production. From 2019 to 2023, investments aimed at diversifying from traditional lumber mills and responding to the increased number of mass timber projects under design have led to a significant growth in the number of plants across North America to supply CLT. There are currently 38 facilities capable of milling mass timber products across the US and Canada [22]. While Canada's production capacity of mass timber products in 2023 amounts to about 12% of the overall production capacity with 9 production facilities, 17 out of the current mass timber production mills in North America are all found west of the Rockies.

Mass timber construction project growth will hence remain dependent on the supply of mass timber products. Currently, the high premium costs of mass timber products are a barrier to more use of CLT and other mass timber building products. In addition, short supply likely to delay construction project closeout makes mass timber construction an alternative many builders end up not adopting. Relying on imported products from Europe, often suggested, does undermine all sustainable positive environmental impacts that mass timber construction brings forward.

3. Mass timber's disruption of the built environment

The introduction of mass timber has disrupted the way we build by stressing a sustainable alternative to traditional construction materials and methods at a time where environmental concerns and the reality of climate change are becoming more pressing, the building sector must change to integrate sustainable practices and materials such as mass timber products recognized to induce lower environmental impacts. Beyond the sustainability impact, mass timber construction has also integrated innovation technology with building information modeling and off-site construction with prefabricated building components.

The construction industry is traditionally slow at implementing innovation and changing practices, including new materials such as mass timber products like CLT. However, the latest trends to watch for in the construction sector for the upcoming few years up to 2027 indicate an accelerated adoption of innovation, particularly building information modeling (BIM) and prefabrication with off-site construction and modular buildings.

In addition, with carbon-neutral or negative targets in terms of environmental impacts across all industry sectors, the built environment must change. Over 40% of the global overall GHG emissions are related to the built environment, and 12% alone are inherent to the material as embodied emissions during the construction phase, while 28% result from the operation and maintenance of buildings. The built environment also consumes 33% of the overall water consumption while generating 35% of overall waste [23]. By comparison to traditional building materials such as steel or concrete, the lifetime emissions for buildings can decrease by as much as 40% when built using products such as CLT [24–26].

BIM, or building information modeling, enables the coordination of all the details in a construction project, including the design and construction drawings. Furthermore, it can deliver a virtual 3D visualization of what the building project would look like, including the superstructure and the various other components, including building services (mechanical, electrical, plumbing). BIM is disrupting construction as it digitizes a project's database to generate predictive data models and specification data such as: 3D images and animation and walkthrough projects; 4D construction scheduling with sequencing of construction or assembly; and cost models in a 5D parametric model. BIM is simply a cluster of all the specifications of a construction project into one digital platform.

To be effective at fast delivery and completion of building projects, mass timber construction projects need to integrate a design for manufacturing and assembly (DFMA) at the get-go of project scoping and initiation. The integration of BIM in the process supports the manufacturing of mass timber products with precision according to the design drawings. Indeed, mass timber products are not simple commodity-building products available on the shelves. Products like CLT panels are manufactured using BIM to extract design data and communicate with the CNC (computer numerical controller) manufacturing tools to deliver customized building products.

Mass timber products such as CLT, bringing challenges and differences to the way we build and construct effectively. For example, a design must be completed before ordering the mass timber product. Additionally, this gives an opportunity to integrate the suppliers as part of the design process and optimize the construction project management. The unique character of mass timber construction projects needing an integration of multiple stakeholders during the construction design and planning phase, from contractors, designers, engineers, suppliers, and installers, could result in

CLT-based buildings built 25–75% faster than similar steel or reinforced concrete on a square footage basis [14, 27]. A faster construction schedule by up to 25% for mass timber projects equates to:

- Less overhead for the general contractor
- Less carrying costs
- Ability to offer early leasing or occupancy

On-site construction for mass timber projects consists of an assembly process. Indeed, the fact that mass timber projects use a DFMA (Design for Manufacturing and Assembly) process requires the completion of all detailed drawings for use for the precise machining and cutting of the mass timber components prior to delivery to the site. The coordination of the manufacturing of the building components tends to extend the design phase of building projects; however, coordination of the construction and assembly sequencing of the mass timber elements requires a JIT (just in time) delivery to the site for large projects to support on-time construction schedules. An effective construction management with the integration of virtual design and construction, all project stakeholders, from owner, architect, engineers, contractor, and supplier, is highlighted by the time-lapse overview of the 18-story hybrid mass timber residence in Vancouver [9]. The latter is another example of how mass timber is disrupting how the built environment is poised to change to provide sustainable and efficient construction.

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Chapter 4

Revolutionizing Wood: Cutting-Edge Modifications, Functional Wood-Based Composites, and Innovative Applications

Jingjing Liao and Mahdi Mubarok

Abstract

Wood stands as a cornerstone of renewable resources, offering sustainability and versatility. Today, its potential is exponentially broadened by creative integration with polymers and resins. This chapter delves into groundbreaking research, starting with a brief wood's intrinsic structure and advancing through commercial wood modification technologies (thermal treatment, chemical modification, and impregnation modification), their characteristics, and industrial perspectives. Furthermore, the chapter introduces advanced modifications of wood structures, focusing on more efficient, scalable, and energy-saving top-down technologies. These innovations will highlight the development of wood composites with futuristic functionalities and diverse applications, such as phase-change energy storage, hydrogels, and transparent wood composites.

Keywords: wood modification, composite, cutting-edge modification, top-down technology, innovative application

1. Introduction

Wood has been used for thousands of years, and has played a vital role in many human activities. As the main component and structural material in trees, wood acts as a bridge between the roots and leaves. The vascular cambium produces it and comprises complex biopolymer composites within a cellular structure, giving it high strength while remaining lightweight. Wood is known for being biodegradable, unique, recyclable, and versatile. Being biodegradable, it can be broken down by organisms like fungi, termites, and bacteria. Its unique physical properties make it useful for various purposes, such as thermal insulation, shock absorption, air purification, and decorative uses. Chemically, wood can be used to produce a variety of organic chemicals (like cellulose, furfural, acetic acid, and benzene-based chemicals), paper, bioenergy, and nanotechnology products (such as nanocellulose).

Some wood products and their by-products are recyclable; for example, wood particles or flakes from sawmills or furniture production can be reused to make particleboard, fiberboard, paper, and paper boards.

Wood is considered a renewable resource, unlike fossil fuels. Renewable resources are seen as one of the best ways to address current and future environmental and resource challenges. Wood is deemed "renewable" if the rate at which it is used or harvested is equal to or less than the rate at which it grows. Following this principle properly would ensure long-term sustainability. To lower the rate of wood harvesting, it's important to develop technologies that recycle used wood products into new ones or for other uses. Additionally, extending the lifespan of wood requires enhancing its properties to better suit its intended purposes.

The current environmental and resource challenges have led to the development of wood modification technology as an alternative solution. Unlike traditional methods that involve using toxic or hazardous chemicals, wood modification enhances the wood's ability to resist such substances. This results in environmentally friendly wood products that are more resistant to decay, have better dimensional stability, and offer improved UV protection, mechanical strength, and fire resistance. This chapter will cover both established lab-scale and industrial wood modification treatments and explore potential future methods.

Additionally, there has been growing interest in wood-based products with special functional properties. This has led to the development of advanced functional wood materials in recent years. The chapter will also discuss recent advancements in functional wood materials and the science behind their unique properties.

2. Basic wood structure

Wood exhibits an anatomical structure. The cross section of wood reveals details about the features from the pith to the bark in the radial and tangential directions. The subdivisions of wood include the pith, heartwood, sapwood, vascular cambium, and bark [1].

The wood cell wall has two main parts: the primary cell wall, which allows for cell expansion, and the subsequent secondary cell walls (S1, S2, and S3), which significantly influence the properties of the cell and wood [2]. Lignin content is highest in the primary wall and middle lamella, decreasing toward the lumen in the secondary walls [1]. The thickest part of the cell wall, the S2 layer, significantly influences the overall properties of the wood [3].

Wood is a composite of cellulose, hemicelluloses, and lignin, with small amounts of extractives and minerals. It is primarily composed of polysaccharides (65–75%) and lignin (18–35%). The chemical composition varies among wood species, with differences in cellulose, lignin, and pentosan content [1]. Cellulose is a linear homopolymer with high molecular weight. It is made up of D-glucopyranose units linked together by β-$(1 \rightarrow 4)$-glycosidic bonds. In wood, cellulose has an average degree of polymerization (DP) of about 10,000 [2]. Cellulose molecules bond to form microfibrils with highly ordered crystalline regions, reaching up to 65% density. Wood cellulose varies in accessibility to water and microorganisms. Crystalline cellulose surfaces are accessible, but the interior is not. Noncrystalline cellulose becomes covered and inaccessible by lignin and hemicellulose. Understanding cellulose accessibility is crucial for its chemical modification, moisture sorption, and interaction with microorganisms [1]. Hemicelluloses are heteropolysaccharides consisting of various sugar units. The average DP for hemicellulose is about 100–200 [2]. The main monosaccharides found in hemicellulose include hexoses, pentoses, and uronic acids. Additionally, smaller amounts of α-L-rhamnose and α-L-fucose may also be present [4]. Some OH groups in hemicellulose are naturally acetylated and methylated, and the structure also contains carboxylate groups compared to cellulose. Hemicelluloses are essential for wood's viscoelastic properties, forming hydrogen bonds with microfibrils and linkages with the lignin. Compared to softwoods, hardwoods contain a higher proportion of hemicelluloses, with different main hemicelluloses in each [2]. Lignin is a complex phenolic polymer primarily composed of phenylpropane units. It forms a random three-dimensional polymer through C–C and C–O–C linkages via a free radical mechanism in nature. Different wood species exhibit a wide variety of lignin structures due to substitutions on the phenylpropane units at α, β, or γ positions. Lignin content in hardwoods ranges from about 18% to 25%, whereas in softwoods, it varies between 25% and 35%. Softwood lignin contains approximately 15–16% methoxyl groups, while hardwood lignin can have up to 21% methoxyl groups [1]. Lignin in the wood cell wall provides rigidity and connects individual cells. It is highly resistant to breakdown [5] and undergoes a transition at around 140°C.

3. Wood modification

As a heterogeneous and anisotropic material, wood varies in chemical compositions, distribution, and cell structures. These properties result in different mechanical characteristics, varying durability against natural degradation, as well as varying swelling and shrinkage behaviors. The need to improve the durability and stability of nondurable woods, especially when exposed to outdoor conditions, has led to a growing trend toward biocide-free techniques based on wood modification techniques, such as heat treatment and chemical modification in the last two decade [6].

Wood modification involves altering wood mainly through chemical, biological, or physical methods to enhance its properties. It is crucial for modified wood to be nontoxic and free from any toxic substances during use, disposal, or recycling. Modifications can be active or passive, with active methods altering the chemical structure. It is essential to ensure no hazardous residues remain after the process, even if hazardous chemicals are used during the modification [1, 7]. **Figure 1** shows an illustration of the effect of thermal, chemical, and impregnation modification in the wood cell wall.

Wood modification involves four main categories: thermal, chemical, impregnation, and surface modification. However, this chapter will focus on thermal treatment, chemical modification, and impregnation modification.

3.1 Thermal modification of wood

By heating wood to specific temperatures, we can change its properties, making it less hygroscopic, altering its color, and increasing its resistance to weathering, dimensional stability, and wood-destroying fungi [8–11]. However, this process may lead to some loss in mechanical strength [12]. Different technologies used vary in their specific conditions and steps, such as peak temperature, duration, and heat transfer mediums, which can significantly impact the outcome [13].

Research has been conducted at various pressure levels, including subatmospheric, atmospheric, and higher pressure environments [14–16]. Different mediums such as

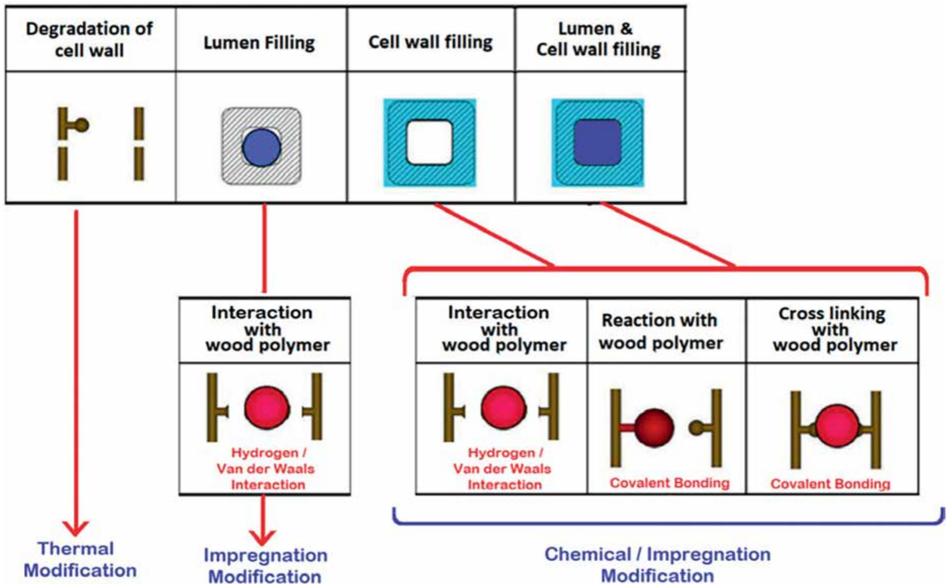

Figure 1.
Illustration of the effect of thermal, chemical, and impregnation modification in the wood cell wall.

hot oil, inert gases, and steam [17–19] are used for thermal modification. For example, the ThermoWood process utilizes superheated steam. Subatmospheric pressure may be necessary for removing volatile organic compounds, but it can hinder heat transfer to the wood. Efficient convective heating systems [20] or conductive heating plates can mitigate this challenge [20, 21].

Among the wood polymers, hemicellulose is highly sensitive to increasing temperatures during thermal modification [1, 22]. The breakdown of the hemicellulose polymer leads to the release of acetic acid, which accelerates further degradation of cell wall polysaccharides [23–25].

3.1.1 Characteristic of thermally modified wood

Thermal modification significantly reduces the wood's ability to absorb moisture [26, 27]. This decrease is due to a reduction in water-accessible hydroxyl (OH) groups resulting from chemical changes during the process [28]. Additionally, the increased cross-linking of lignin-carbohydrate complexes restricts the wood's capacity to absorb water between cellulose chains [23].

Thermally modified wood has improved dimensional stability compared to untreated wood due to reduced swelling, which can be attributed to structural changes, alterations in lignin-carbohydrate complexes, and the bulking effect caused by the filling of cell wall micropores with by-products from thermal degradation [29, 30].

A wood's mechanical properties, influenced by factors like anatomy, density, and moisture content, are generally reduced in thermally modified wood. Tensile strength is notably affected, followed by shear and compressive strength [31, 32]. If the mass loss is below 20%, bending strength can decrease by 50–60% from its original value [33, 34]. Bending strength decreases significantly, but in some cases, it may increase, especially with mild thermal modifications [35, 36]. The reduction in hygroscopicity of thermally modified wood can partially offset the decrease in strength [34, 37].

The modulus of elasticity (MOE) is minimally impacted by thermal modification, and in some cases, it may even have a higher value than the original due to increased wood stiffness [34–36].

Thermal modification improves wood resistance to fungal decay by reducing mass loss after exposure to fungi. The process parameters such as peak temperature, duration, and mass loss influence decay resistance [38–40]. Significant improvements in durability can be achieved, although some mechanical properties may decrease [41]. The type of raw material used also affects the decay resistance of thermally modified wood [39]. However, in soil contact tests, thermally modified wood has shown insufficient durability [42]. Changes in chemical composition, including degradation of hemicellulose and modification of wood polymers, are believed to improve decay resistance. Additionally, hindrance to wood cell wall penetration and the formation of stable-free radicals during thermal modification contribute to the wood's resistance against degradation [39, 43–45].

3.1.2 Industrial perspective

Wood thermal modification has been utilized in industry for many years, resulting in the availability of numerous thermally modified woods in the market. These woods are produced using different methods such as ThermoWood®/Premium wood (Finland), Les Bois Perdure retification (France), Plato process (Netherlands), VAP HolzSysteme® (Brazil), Oil Heat treatment (Germany), Westwood process (America), and FirmoLin® technology (Netherlands). While these woods offer enhanced durability against decay, they do not provide sufficient resistance to termites, especially in soil contact, necessitating the need for substantial improvement. In response to this limitation, Mubarok et al. [46, 47] have combined thermal modification with mild chemical modification using glycerol maleate. After a 1-year field test study in Indonesia, it was demonstrated that these thermochemically modified woods exhibited significantly better durability properties compared to woods that had only undergone thermal modification. These findings underscore the continuing challenge of further advancing thermal modification technology.

3.2 Chemical wood modification

Chemical modification aimed at improving wood resistance against decay, marine organisms, and termites, as well as increasing dimensional stability, relies on the effective distribution of impregnated chemicals within the water-accessible regions of the cell wall. It is crucial that the wood-modifying chemicals are capable of swelling the wood, facilitating penetration and reaction with the hydroxyl groups of the wood cell wall polymer at temperatures at or below 120°C. Numerous studies have investigated chemical wood modification, some of which have been reviewed in reliable literature sources [2, 48–50]. These include esterification, acetal formation, etherification, acrylonitrile, and epoxides method [48]. Improved dimensional stability and biological resistance of the modified wood are commonly achieved by these chemical modification techniques.

The characteristics observed in chemically modified wood include an increase in wood volume relative to the volume of the added chemical, resistance of the added chemical to leaching, and new absorption in infrared data. However, due to several considerations, only certain chemical wood modification techniques can be implemented on an industrial scale. These techniques include wood acetylation, wood furfurylation, resin impregnation, and surface charring wood.

3.2.1 Acetylation

The process of wood acetylation was first developed by Fuchs [51]. It involves treating spruce wood with acetic anhydride and sulfuric acid as a catalyst. Acetylated wood, a resulting product, is formed by reacting the wood with acetic anhydride (**Figure 2**) [2, 52, 53]. Sometimes, an acid catalyst like sulfuric acid is needed to initiate the reaction by protonating the oxygen carbonyl and activating the carbocation of the acetic anhydride. Other catalysts for this reaction have been summarized by Rowell [48], including pyridine, zinc chloride, urea-ammonium sulfate, sodium acetate, dimethylformamide, trifluoroacetic acid, magnesium persulfate, boron trifluoride, and gamma rays. Furthermore, the reaction has been carried out with an organic cosolvent or without a catalyst [54, 55]. Reactions with acetic anhydride in a gas phase have also been documented, but the diffusion rate is extremely slow, thus limiting this technique to thin veneers [56].

The reaction that occurred in wood acetylation is called a single-site reaction, which means that one acetyl group binds to one hydroxyl group without any polymerization taking place. The total increase in weight due to acetylation can be directly correlated with the number of hydroxyl groups that have been blocked [48]. In addition, the permanent absorption of acetic groups is affected by factors such as temperature, reaction time, and the use of initiators or swelling agents [48].

3.2.1.1 Characteristic of acetylated wood

Acetylation involves replacing a hydroxyl group with an acetyl group, leading to increased size and reduced water vapor absorption in wood cell walls. This process improves resistance to wood decay fungi and dimensional stability. Experiments show that larger substituted groups reduce water vapor absorption more effectively. Polarity of the side groups also affects absorption levels [44, 57].

The exceptional resistance of acetylated wood to fungi can be attributed to the alteration in the conformational structure of arabinose, impeding the breakdown of hemicellulose [58]. Additionally, the reaction delay in the chelator-mediated Fenton (CMF) due to brown rot decay before enzymatic degradation has been observed [59–61]. Nevertheless, it's important to note that certain metabolites from fungi and enzymes involved in degradation of wood remain active even in some modified wood, with the capability to remove highly acetylated wood polymers or cleave acetyl groups from polymers [60, 62]. Furthermore, comprehending the moisture

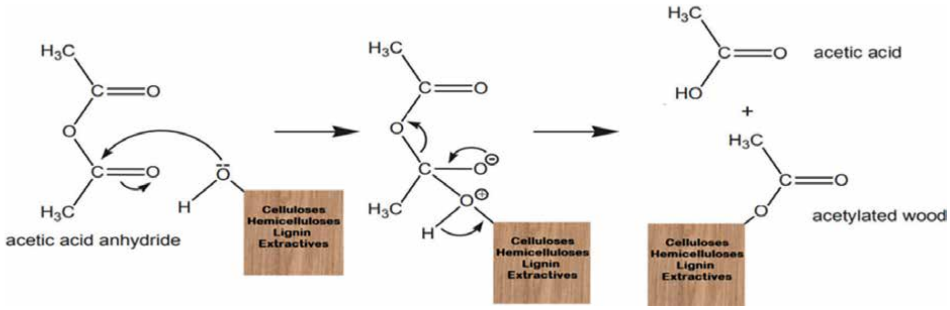

Figure 2.
General reaction mechanism occurred during wood acetylation.

exchange between wood, fungus, air, and soil in standard soil bottle tests, including active transport, presents a significant challenge in investigating the cause of the moisture reduction mechanism in acetylated wood, which can protect against fungal degradation [50].

3.2.1.2 Industrial perspectives

Until now, the current preferred method for acetylating wood involves using a limited quantity of acetic anhydride liquid without the addition of a catalyst or cosolvent [48]. This process was commercialized in the early 2000s by Accsys Chemicals in the Netherlands [2]. In 2021, Accsys's sales volume for this product under the trade name ACCOYA® reached 60,466 m^3 per year and is estimated to reach 200,000 m^3 per annum in 2025 [63].

Although wood acetylation has undergone extensive research and is now readily available commercially, there remain unexplained reasons regarding how it preserves wood. Gaining a deeper knowledge of these phenomena has the potential to enhance the commercial process, resulting in improved cost-effectiveness. Developing a method that enables the targeting of acetylation to modify specific areas of the cell wall near the cell lumina is a recent breakthrough from Digaitis et al. [64], opening the door for further experiments to explore the role of acetylation in wood protection.

3.3 Impregnation modification

The wood impregnation modification technique involves saturating the wood cell walls with specific chemicals to create a material locked into the wood cell wall. The primary objectives of this treatment are to restrict water penetration and reduce decay. Various chemicals have been studied for this purpose, but only a few treatments have been viable for industrial-scale implementation, such as furfurylation and 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU) treatments [7, 65].

3.3.1 Furfurylation

Derived from hydrolyzed biomass, furfuryl alcohol (FA) serves as a renewable main agent for furfurylation of wood. Essentially, the key characteristics of furfurylated wood hinge on the retention and polymerization of FA within the wood structure. The furfurylation of wood, originally developed in the 1950s, has evolved over time. Researchers initially used zinc chloride as a catalyst, but this caused issues with cellulose degradation and uneven treatment [66]. Maleic anhydride has since been suggested as a replacement catalyst [67, 68]. Recent studies have explored the use of citric acid and other weak acids as initiators in furfurylation [66, 69, 70]. Additionally, the choice of solvent used affects the cross-linking during curing and the modified wood's properties. Research results regarding the use of different solvents have been demonstrated, with some studies showing differences in polymerization, while others did not [71, 72].

It is believed that during wood furfurylation, FA binds to other FA molecules, forming a furan homopolymer in the wood's channels and becoming entangled within the cell walls. It also cross-links to lignin (**Figure 3**), although the existence of such bonds has only been proven in vitro for lignin model compounds, not in situ [73, 74].

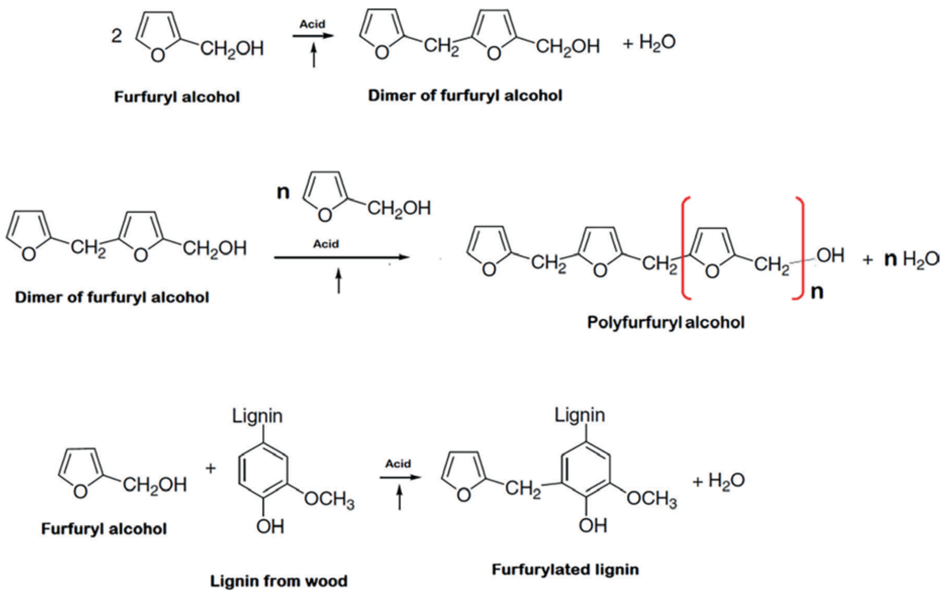

Figure 3.
The main polymerization reaction of furfuryl alcohol and its reaction with lignin (modified scheme adopted from Gérardin [65]).

3.3.1.1 Characteristic of furfurylated wood

Multiple studies have shown that furfurylation treatment improves wood's dimensional stability in fluctuating humidity conditions [75, 76]. The process also reduces the equilibrium moisture content (EMC) of wood to around half of untreated wood at a specific moisture level [77]. Higher dimensional stability of furfurylated wood was also proven after submission in the water [70].

Furfurylation protects wood from fungal degradation, as demonstrated across various wood and fungal species [66, 78]. Even under aggressive brown rot strain with continuous water access, the mass loss in earlywood samples within the first few weeks was limited to 10–15% [79]. Furfurylation, unlike acetylation, increases wood cell wall bulk without consuming hydroxyl groups. This reduces space for water, slowing down fungal decomposition, making it an effective wood protection method [44, 80]. This resistance is also attributed to furfurylation possibly making part of the wood's lignin more resistant to the fungal oxidative tools [78].

In the context of termite resistance, numerous studies have highlighted the effectiveness of furfurylated wood in withstanding these pests [66, 81, 82]. Nevertheless, these studies overlooked the crucial factor of potential leaching of the wood samples prior to the termite feeding trials. A substantial reduction in the protective effect of furfurylation when the wood had been leached before the feeding trial has been reported [83]. This outcome validates previous findings indicating leaching from furfurylated wood due to inadequate curing [84]. In addressing this matter, Mubarok et al. [70] have enhanced the system by incorporating tannin into the FA solution, resulting in improved resistance to leaching in furfurylated wood (**Figure 4**).

Furfurylation delays marine deterioration, especially with shipworm and gribble [85]. Material hardness likely plays a role in making the material more difficult to ingest for the animals [86]. A nonrecognition of modified wood by the enzyme

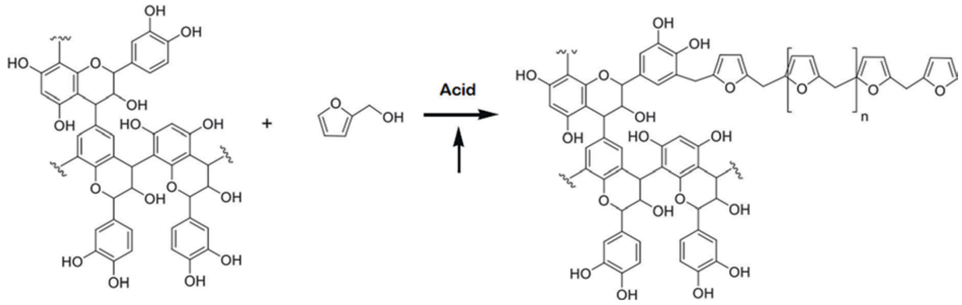

Figure 4.
Main possible reaction of furfuryl alcohol and tannin.

during digestion might also be the reason in this case [85]. The choice of impregnation solvent also affects durability. Wood furfurylated in alcohol with weight percent gain (WPG) 29% remained sound after 16 years, while water-furfurylated samples failed in 8 years [87].

3.3.1.2 Industrial perspectives

The first commercial wood furfurylation plant was Kebony® AS, established in 2009 in Skien, Norway, with a capacity of 20,000 m^3/year. Another plant is now in Antwerp, Belgium. Foreco Dalfsen in the Netherlands also produces NobelWood® (1000 m^3) from radiata pine using prepolymerized FA resin [49]. VisorWood for softwood modification (20–40% WPG) was also created. Kebony offers Kebony 30 (10–50% WPG) and Kebony 100 (70–100% WPG) options for hardwood [2, 65]. However, this cutting-edge technology currently serves a niche market due to its premium pricing.

For competitive use, efforts have been made to minimize the cost of furfurylation, such as using humins derived from biorefining plant biomass as an alternative to FA, which requires less demanding curing conditions [88], and employing the gas phase furfurylation method to effectively polymerize FA in wood cell walls [89]. Additionally, the use of specific substances during the furfurylation process results in a less brittle product of furfurylated wood machining, representing another improvement that can be applied to this existing furfurylation technology [71, 90].

Lately, adding tannin to the FA solution could be a promising option for enhancing the leaching resistance of furfurylated wood on a larger scale. This addition of tannin can also improve the reactivity of the less acidic organic acid, extend the stability of the FA solution, as well as increase the biological durability of furfurylated wood and potentially reduce its characteristic odor [91].

3.3.2 Wood modification based on resin/other polymerization reaction

Water-soluble thermosetting resins have been extensively researched for both solid wood [92] and wood-based panel [93] applications over the past few decades. The use of thermosetting formaldehyde resins for modifying wood began in the mid-twentieth century [94, 95]. Specifically, low molecular weight phenol formaldehyde (PF) and melamine formaldehyde (MF) resins, as well as cyclic N-methylol compounds like DMDHEU, have been used for this purpose [96]. These resins are considered “active modifications” because they chemically alter the wood through polymerization. The process involves two steps: first, fully impregnating the wood with the resin mixed in a solvent under vacuum or pressure, and second, allowing the resin to react and fix within the wood structure. Temperatures between 120°C and 140°C are recommended for the reaction to complete [97]. The speed of the resin's polymerization during heat curing can be influenced by the pH of the resin solution, the wood's acidity [98], and, sometimes, the use of initiators [99].

Thermosetting resins used in wood modification have special properties that allow them to penetrate the water-swollen wood cell wall, causing the wood to bulk up [100, 101]. During heat curing, the solvent evaporates, and the resin monomers and oligomers polymerize, becoming water insoluble and securely fixed within the wood. Co-condensation might occur between DMDHEU resin and cell wall components [102], but evidence of strong covalent bonds is limited [103]. On the other hand, MF and PF resins are believed to stay in the wood mainly through mechanical processes like entanglement during self-condensation [104, 105]. The form and curing of the polymerized resin are influenced by factors like reactive functional groups, the ratios of the reactants, temperature, moisture levels, and pH [106, 107].

3.3.2.1 Characteristic of wood modified by resin

Various studies on resin-impregnated wood show that the modified wood using this method can also improve its dimensional stability [108], mechanical properties [103, 109], and durability against biological degradation [110, 111]. A micropore blocking, reduced accessible hydroxyl groups, and lower cell wall moisture content as key factors in reducing the degradation rate of decay fungi in resin-treated wood were identified as factors for their resistance against fungi [59]. Further, the location of resin molecules within the cell wall also improves this decay resistance [109].

3.3.2.2 Industrial perspective

Wood treatments using thermosetting resins like PF, MF, and DMDHEU have been extensively researched. Impreg™ can be made from melamine-, phenol-, or urea-based resins, while Compreg™ is made from phenol-formaldehyde resins. These resins are cured under mild alkaline and acidic conditions and can be incorporated with a monomer such as styrene or methyl methacrylate to harden through a stepwise polymerization mechanism [96]. Unfortunately, MF and PF resins can change morphology during storage, affecting shelf life and wood penetration, intriguing further research on the reusability and aging behavior of these resins.

Another current wood modification based on resin impregnation has been performed by Mubarok et al. [70], using commercially available polyamine and polyepoxy resin impregnated into the wood followed with relatively low curing condition at 103°C. This resin-modified wood exhibited better resistance against leaching, better durability against decay, and better hardness performance.

4. Functional materials derived from wood

For decades, wood modifications have primarily focused on addressing wood's natural limitations, such as improving its resistance to decay, enhancing dimensional stability, protecting it from UV light, and making it more fire-resistant for use in buildings and furniture. However, in the past decade, there has been a significant rise in projects and research aimed at creating advanced functional materials from wood. This progress is driven by two key factors: a push to develop high-performance materials from renewable resources and growing interest in wood as a material. Wood's unique porous structure, which varies from the nano- to the macroscale, shows great potential for creating functional materials when combined with nanoparticles, polymers, metals, or metal-organic frameworks [112–114].

There are two primary methods for creating wood-based functional materials. One approach involves directly applying functionalization treatments to the wood, while the other involves obtaining the cellulose framework through structure-preserving delignification before functionalization. These top-down methods differ from the usual bottom-up processes by directly using wood, which eliminates the need for disassembly and reassembly. This makes it a simpler, more scalable, and energy-efficient way to develop functional wood composites. In this section, we will briefly discuss recent developments in wood-based functional materials. These include phase change energy storage wooden composites, wood aerogel, wooden composites hydrogel, and transparent wooden composites.

4.1 Phase change energy storage wooden composites

Phase change energy storage wooden composites, mainly applied as energy-saving building materials, can be easily developed by filling various phase changing materials in wood matrix via a vacuum impregnation method. Commonly, the phase change working substances can be divided into organic phase materials (e.g., paraffin, fatty acids, octadecane, and polyethylene glycol) [115], inorganic polymers (e.g., magnesium nitrate hexahydrate) [116], or their mixtures (e.g., capric and stearic acid) [117]. Numerous wood species can be used as matrices for preparing phase change energy storage wooden composite [118]. However, wood with low density and high porosity structures are considered more beneficial for embedded amount and types of phase change materials. For example, Hartig et al. reported the impregnation of four wood species (beech, poplar, oak, and spruce) with a paraffinic phase change material; poplar presented 480 kg/m^3 deposition of paraffinic, while oak had only 100 kg/m^3 deposition [119]. On this basis, balsa has become one of the most widely reported woods to develop wooden composites with high phase change material loading due to its smallest density and most porous anisotropic structure [120]. Especially, wood matrix pretreated by a delignification and/or carbonization process will simultaneously ameliorate liquid leakage issue, promote the impregnation rate, and enhance the thermal conversion efficiency of PCMs [121, 122].

4.2 Wooden composite hydrogels

Wooden composite hydrogels (WCHs) can be initially achieved by delignification process to remove up to 95% and 75% of initial mass of lignin and hemicellulose using chemical reagents like hydrogen peroxide, sodium sulfate, sodium hydroxide, or acetic acid [123]. The retention of porous cellulose skeleton provides a natural hierarchical/anisotropic wood structure and active sites to interact with other polymers at molecular level for the construction of WCHs with reliable mechanical properties and good antiswelling capacity. Their extending functionalities can be achieved by incorporating with various hydrophilic polymers and using different cross-linking strategies. Vacuum impregnation and in situ polymerization allow the pristine acrylic acid precursor solution to fill matrix pores and guarantee the cross-linking of hydrogel and interact with cellulose [124]. Metal ions (Fe^{3+} ions, Zn^{2+} ions) help to promote the mechanical performance and ionic conductivity of WCHs by suffering a double cross-linked reaction inside structure-remained cellulose scaffold for constructing sensors and flexible electronics [125]. As reported by Yan et al., Fe^{3+} ions and the catechol groups in lignin can rapidly induce the self-gelation of polyacrylamide hydrogel in the presence of an initiator. This process forms dynamic bonds that give the wood composite hydrogel (WCH) anisotropic properties, along with toughness and flexibility, making it highly sensitive for pressure sensing applications [126]. A two-dimensional and conductive MXene with aid of Zn^{2+} ions enhanced the network bonding and high conductivity of a wood hydrogel [127]. For the applications of tissue engineering that require specific mechanical properties, an anisotropic wood-hydrogel composite was fabricated by infiltrating delignified spruce wood with gelatin solution by using glutaraldehyde. By adjusting cross-linking reaction time, wooden composite hydrogels have tunable strength range 1.2–18.3 MPa and stiffness range 170–1455 MPa [128].

4.3 Transparent wooden composites

The transparent wood composites can be prepared using top-down method by introducing transparent polymers with suitable refractive indices into delignified wood scaffold with matching refractive index for achieving optical transmittance and adjustable optical haze [129]. The most widely used polymers include epoxy resin, poly(methyl methacrylate), polyvinylpyrrolidone, n-butyl methacrylate, n-butyl methacrylate, polystyrene, etc. [130]. However, high optical transparency wooden composites are still a challenge in optical applications like smart window, and passive flexible display. The hydrogel developed from poly(acrylic acid) and delignified wood only presents optical transmittance when the water content is lower than 80% [131] due to the mismatching refractive index between water and wood hydrogel matrix. One solution can be the posttreatment of delignified wood using NaOH or TEMPO-mediated oxidation for enhancing the interface between wood and optical transmittance polymers [132]. The undesirable optical transmittance can also be attributed to cellulose microfibrils, which tend to aggregate easily during the drying and rehydration processes in hydrogel preparation. Wang et al. report an innovative method for maintaining the cellulose nanofibril alignment and nanoscale individual nanofibrils dispersion for preparing a strong, transparent and thermochromic wood composite hydrogel. This transparent wooden composite has a pretty high optical transmittance (85.8%) with anisotropic light scattering behavior even under 94.9 wt% water content by TEMPO-mediated oxidation of delignified wood followed by in situ polymerization of poly(N-isopropylacrylamide) [132]. As poly(N-isopropylacrylamide) is a typically heat-sensitive polymer, such transparent wooden composite can be used for the application of smart windows because it transforms into an opaque state when poly(N-isopropylacrylamide) hydrogel reaches the transition temperature [133]. These transparent woods infiltrated with some functional additives (rare-earth strontium aluminum oxide) show attractive color-tunable and glow-in-the-dark colorless capacity for smart building [129, 134].

Apart from the mentioned wooden composites, the researchers are continuing to develop functional wood-based materials from wood using an efficient “top-down” method combined with physical, chemical, and nanotechnology, such as room temperature phosphorescent [135], wood aerogel [136], and ionogels [124], transforming wood as the next-generation structural and functional materials for a sustainable future.

5. Conclusion

For two decades, wood modification has become an alternative solution for improving wood quality, specifically its durability against various wood-degrading organisms, such as fungi and insects, instead of using conventional poisonous or hazardous chemicals or preservatives in the past. Dimensional stability and sometimes mechanical properties also increased due to this modification. Numerous researches on wood modification have been investigated and reviewed; however, only some of them are feasibly implemented. To date, the use of modified wood, particularly chemically modified wood and wood impregnation modification, is only for the niche market segment. Out of this reality, research on wood modification focused on environmentally friendly treatments still needs to be improved, demanding extensive further investigation and being driven explicitly for mass production. Besides this, several innovations in wood composites as functional materials have begun to thrive today, serving various advanced applications, such as phase change energy storage, hydrogel, and transparent wooden composites previously discussed. However, implementing these functional materials derived from wood, especially for mass production, is also challenging and requires further investigation.

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Chapter 5

Green, Sustainable, and Circular Forest Products

Cong Mao, Yuan Lin, Yue Pan, Lei Qin, Ming Cao, Suyong Huang, Chunlei Dong, Wei Gao, Xiaojian Zhou, Linkun Xie, Guanben Du and Hui Wan

Abstract

In this book chapter, we first provided a concise overview of global forest products and their impacts and benefits. Then, we introduced the theory of green, sustainable, and circular forest products to our readers. Through a literature review and theoretical framework, we have presented several case studies regarding the development of green, sustainable, and circular forest products globally, focusing on raw materials, process control, and panel qualities. Based on the definition of the theory, we have analyzed and highlighted are as within the forest products sector, including production, market, research, and education that require enhancement and improvement. Finally, we have shared our perspective on the future development of the forest products industry.

Keywords: circular forest products theory, direction, future development, green, life cycle analysis, panel qualities, process control, raw materials utilization, recycle, sustainable, standard

1. Introduction

1.1 Overview of the global status of forest products

The global forest products market exhibits a trend toward diversified development. In 2018, the total consumption of round wood in the UN Economic.

Commission for Europe (UNECE) region was estimated at 1.4 billion cubic meters, representing an increase of nearly 5% compared to 2017. Over the 5–year period ending in 2018, the apparent consumption of round wood for industrial purposes in the UNECE region showed an upward trend, reaching 1.19 billion cubic meters, which was 5.1% higher than in 2014. In 2017, the consumption of wood fuel increased by 3 million cubic meters, reaching 221.5 million cubic meters. Of the total round wood harvested in the UNECE region in 2018, approximately 18% was used for fuel (257.1 million cubic meters), an increase of 9.2 million cubic meters (+3.7%) compared to 2017. In 2017, Europe accounted for 54% of the total wood fuel consumption in the UNECE region [1].

Within China, the forest products industry chain continues to extend, encompassing sectors such as timber, pulp, paper, and composite panels. In recent years, with heightened environmental awareness and policy support, domestic forest products enterprises have made notable progress in technological innovation, green production, and resource utilization efficiency [2]. Moreover, there is a growing demand in the domestic market for high-quality, environmentally friendly forest products, driving industrial upgrading and transformation.

In the international forest products market, North America and Europe are primary regions for timber production and export, whereas the Asia–Pacific region is a major import market. Due to the global emphasis on sustainable development, forest certification systems (such as FSC and PEFC) have gradually become widespread, ensuring the sustainability and legality of forest product production [3]. However, the global forest products industry and markets still face challenges, including over–exploitation of forest resources, impacts of climate change on forest ecosystems affecting timber yield and quality, and trade frictions impacting the effective utilization of timber. These factors inspire countries to strengthen coordination in international cooperation and policy formulation to further promote the sustainable development of the global forest products industry.

As can be seen, traditional methods of forest product production are facing severe challenges. Unsustainable logging and forest degradation not only threaten biodiversity but also exacerbate environmental deterioration. Thus, the concept of green, sustainable, and circular forest products (CFP) emerges to address these challenges.

1.2 Impacts of forest products on the environment

While the global forest products industry drives economic development, it also boasts many environmental advantages due to the inherent features of wood and forests, especially when adopting sustainable management and production methods. These advantages include carbon storage and absorption, biodiversity conservation, reduction of environmental pollution, and efficient resource utilization [4]. Meanwhile, people are also becoming aware that over–harvesting and illegal logging will lead to forest degradation, loss of biodiversity, greenhouse gas emissions, water resource depletion, and deterioration of soil conditions.

Furthermore, the low material utilization rates, high energy consumption, and pollutant emissions during traditional wood processing also have a certain adverse impact on the environment.

1.2.1 Environmental benefits brought by forest products

1.2.1.1 Carbon storage and absorption

Forests act as carbon sinks, absorbing carbon dioxide (CO2) through photosynthesis and storing it in biomass and soils. It is estimated that global forests annually absorb CO2 equivalent to roughly one–third of human activities emissions [5]. This stored carbon can remain locked away long–term in wood products, meaning that converting trees into wood products, such as furniture and building materials, can sequester CO2for extended periods. Healthy forests continuously absorb atmosphericCO2, fixing carbon through growth processes and aiding in mitigating climate change. Restoring degraded forests and implementing reforestation projects can further enhance carbon uptake capacity.

1.2.1.2 Biodiversity conservation

The development of sustainable and CFP plays a significant role in habitat preservation. Sustainable forest management provides habitats for diverse species, conserving large numbers of flora and fauna, maintaining ecosystem health, and stability [6]. By creating and maintaining ecological corridors, connecting different natural habitats, and promoting biodiversity conservation and species migration, sustainable forest management ensures forest health. Sustainable forests, through water conservation, regulate the hydrological cycle, prevent soil erosion, protect water quality, further anchor soil, prevent wind erosion, and maintain soil fertility and structure, ensuring conditions for further forest and forest products development.

1.2.1.3 Reduction of environmental pollution

The use of sustainable and CFP can replace chemicals that have a greater environmental impact, such as chlorine–free bleaching and bio–based adhesives, reducing the use and emission of harmful chemicals [7]. Utilizing low–carbon logging techniques [8] reduces damage to forest ecosystems and minimizes the pollution of soils and water bodies. Additionally, through waste recycling and reuse [9], the recovery and recycling of old wood and paper products reduce land filling and incineration, lowering environmental pollution. Last, using waste from wood processing and papermaking as biomass energy [10] reduces waste emissions and the use of fossil fuels.

1.2.1.4 Efficient resource utilization

Forest resources are renewable, and through scientific management and rational use, a sustainable supply can be ensured [11]. For instance, cultivating fast–growing forests: planting fast–growing species like Eucalyptus and Poplar has provided society with the timber needed for development in a short time, alleviating pressure on natural forests crucial for environmental protection. Simultaneously, optimizing the forest products production processes: adopting advanced technologies like efficient sawing and high–frequency drying lowers wood deformation, increases lumber yield and utilization and reduces resource waste. At the end of the service cycle of forest products, promoting the recycling of wood and paper products, constructing a CFP system, and extending the life of forest products further enhance resource utilization efficiency.

1.2.1.5 Replacement of high carbon emission materials

In terms of building materials, wood, compared to other materials like steel and concrete, has lower carbon emissions during production [12]. Through modern timber construction techniques, such as cross–laminated timber (CLT) [13], wood becomes viable for high–rise buildings, assisting the construction industry in lowering its carbon footprint. Wood and other forest products can substitute petro–based materials, like plastics and chemical products, reducing consumption of fossil–based materials and lowering carbon emissions in their production. Additionally, the biodegradability of forest products reduces pollution from nonbiodegradable materials like plastics.

1.2.2 Negative environmental impacts brought by the forest industry and forest product production

Negative impacts of forest products on the environment contribute to forest degradation and a decline in forest cover, with global forest area showing a linear downward trend [14]. In 2019, the global forest stock was 3825 million hectares, projected to decrease to 3815 million hectares by 2025.Accelerated industrialization in various countries affects the global environment, leading to issues such as climate change, expansion of desert areas, and increased soil erosion, directly or indirectly causing a gradual shrinkage in global forest areas.

1.2.2.1 Forest degradation and decline in forest cover

Global forest cover has been declining. Taking the Amazon rainforest in Brazil as an example, deforestation has been increasing since 2012. Excessive logging and illegal deforestation have led to extensive forest degradation and a decline in forest cover, recently at record–breaking rates. According to data from Brazil's National Institute for Space Research, the average annual deforested area of the Amazon rainforest exceeds one million hectares [15]. This massive deforestation not only disrupts the balance of ecosystems but also reduces the carbon sink capacity of forests, exacerbating global climate change.

In Indonesia, vast tracts of tropical rainforest have been cleared for palm oil plantations. According to data from the Global Forest Watch organization, Indonesia lost approximately24 million hectares of tropical rainforestbetween2001 and 2019 [16]. Many of these deforested are as were primary forests with irreplaceable ecological functions.

1.2.2.2 Loss of biodiversity

Mangroves in Malaysia face threats from the expansion of commercial aquaculture, agriculture, urban development, and natural processes associated with climate change, leading to significant destruction. According to data from the International Mangrove Conservation Organization, Malaysia's mangrove area has been reduced by over 30% in the past 50 years [17].

The Congo rainforest, Africa's largest tropical rainforest, harbors rich biodiversity.

However, due to illegal logging and infrastructure construction, the living environments of many endangered species are severely threatened [18].

1.2.2.3 Greenhouse gas emissions

The production and processing of forest products generate greenhouse gases.

Forest fires are particularly noteworthy. Forest fires in Canada are not only natural phenomena but also linked to climate change and human factors. In 2017, British Columbia, Canada, experienced large–scale forest fires, consuming over 1.3 million hectares of forest [19]. The fires released large amounts of carbon dioxide, significantly increasing greenhouse gas emissions. According to data from Canada's Ministry of Environment and Climate Change, the carbon dioxide emissions from this fire equaled 10% of the province's annual emissions.

Russia possesses the world's largest forest reserves and is a major exporter in the global timber market [20]. Russia's main trading specialty is logs and semi finished wood and paper products. Timber processing requires substantial energy, particularly in drying and transportation. It is estimated that Russia's timber processing industry emits nearly20 million tons of carbon dioxide annually.

1.2.2.4 Water consumption and pollution

In the United States, the pulp and paper industry is a major water consumer.

Producing one ton of pulp consumes approximately 100 cubic meters of water. Such substantial water consumption poses challenges to local water resource management and may exacerbatewater scarcity issues. According to the U.S. Environmental Protection Agency, the pulp and paper industry is the third–largest industrial water user in the U.S., trailing only the chemical and food processing industries [21].

1.3 Examples of benefits brought by the forest and forest products industry

Here are a few examples:

Finland is a global leader in timber and pulp production, with its forest products industry generating substantial economic gains [22]. According to data from Statistics Finland, in 2019, the export value of Finland's forest products reached 13 billion Euros, accounting for 20% of the country's total exports. The forest products industry directly and indirectly provided approximately 160,000jobs, comprising 6% of the national employment total. In technological innovation, Finland's forest products industry places great emphasis on innovation, collaborating with universities and research institutions to continuously enhance production efficiency and product quality. Finland's Technical Research Center collaborates with companies to develop novel bio–based materials, driving the high–value–added applications of forest products and laying the foundation for sustainable cities [23].

Community forestry projects in British Columbia, Canada, demonstrate the positive social impact of forest products. These projects permit local communities to manage and utilize surrounding forests. Community empowerment through community forestry projects allows residents to participate directly in forest resource management and decision–making, strengthening community autonomy and improving living environments, bringing significant social benefits. The Harrop–Procter Community Forest project in British Columbia implements sustainable forest management plans through community collaboration [24]. In come from selling timber and other forest products enables communities to invest in public infrastructure, education, healthcare, and other areas. Community forestry projects also raise environmental awareness and ecological knowledge among residents through education and outreach activities. Regular forest ecology workshops educate community members on participating in sustainable forest management.

To mitigate the rapid climate change trend, many countries will increase their demand for forest biomass energy raw materials. However, only by considering local conditions and effectively linking energy use with resource bases through design and planning can the sustainable utilization of forest biomass resources be ensured.

Lithuania has achieved notable success in producing bioenergy from forest resources [11], converting wood waste and byproducts into biofuel, effectively reducing dependence on coal and oil, and cutting hundreds of thousands of tons of carbon dioxide emissions annually. According to data from its energy agency, bioenergy accounts for over 30% of the country's total energy consumption, aiding Lithuania in achieving its climate goals.

Brazil's Amazon Rainforest Restoration Project showcases human capabilities and determination in ecological restoration. Through promoting sustainable forestry practices and reforestation projects [25], Brazil has successfully restored vast areas of degraded forests. These activities have enhanced carbon sink capacity: Reforestation projects boost the carbon sink capacity of forests, contributing to addressing global climate change; secondly, they have kept biodiversity conservation. In reforestation projects in the Amazon region, extensive primary forests have been restored, providing new habitats for various endangered plant and animal species. Through afforestation, significant reductions in soil erosion and improvements in local water resourcemanagement havebeen achieved.

2. Concept of green, sustainable, and circular forest products

2.1 Definition of green, sustainable forest products

Forest products refer to goods produced from forest resources, categorized into woody and non woody forest products. Woody forest products are divided into eight categories: logs, sawn timber, wood composite panels, wood products, paper, furniture, wood chips, and other items. Non woody forest products are classified into seven categories: seedlings, bamboo shoots, mushrooms, fruits, wild vegetables, coffee, tea, spices, tonics, medicinal herbs, forest chemical products, cork, and rattan.

Green, sustainable forest products [26] are those that have minimal environmental impact throughout their entire lifecycle, efficient resource utilization, and sustain–ability. They ensure the renewability of forest resources and the health of ecosystems through sustainable forest management and eco–friendly production and processing techniques, while meeting social and economic development needs.

2.1.1 Sustainable forest management (SFM)

The production of green forest products relies on forests certified under sustain–able management. SFM ensures that forests can rapidly regenerate after harvesting and maintain their ecological functions.

Although the principles of sustainability have a relatively long history in Europe, the widely recognized definition of SFM was only established in 1993 throughthe European Forest Process, subsequently adopted bythe FAO [27]. It defines SFM as "the management and use offorests and forest lands at a rate and in a manner that maintains their biological diversity, productivity, regeneration capability, vitality, and their potential to fulfill, now and in the future, relevant ecological, economic, and social functions at local, national, and global levels without causing damage to other ecosystems." This implies that SFM can be described as seeking a balance between meeting the growing demand for forest products and services and protecting forest health and biodiversity.

The core principles of SFM are [28]:

Ecological sustainability: SFM is dedicated to protecting and maintain the biodiversity of forest ecosystems, including plant, animal, and microbial species. Protecting biodiversity helps maintain the health and stability of ecosystems and ensure the ecological functions of forests, such as water source conservation, soil protection, and carbon storage, to continue to function effectively.

Economic sustainability: Through scientific management and reasonable harvesting, ensure the sustainable use of forest resources, enable them to provide timber and other forest products over the long–term, diversify forest industries, such as non–timber forest products (medicinal plants, fruits, etc.), ecotourism, etc., and increase the economic benefits of forests.

Social sustainability: Encourage and support local communities in participating in forest management, ensure their interests and rights in the decision–making process, promote social fairness and stability, respect and preserve the cultural and traditional values within forests, and protect the cultural heritage of indigenous peoples and local communities.

2.1.2 Eco-friendly production and processing techniques

Eco–friendly production and processing techniques aim to reduce resource consumption, lower pollution emissions, and improve energy efficiency, thus achieving sustainable development goals. In the forest products industry, many innovative and improved processes and technologies are applied to wood processing, pulp and paper production, and other sectors.

2.1.2.1 Wood processing

Efficient sawing technology: Optimized sawing using computer–controlled sawing technology to maximize timber yield by optimizing sawing paths and angles, reducing waste [29].

Laser sawing: Using laser cutting technology for wood processing, offering advantages such as high precision, low energy consumption, and reduced wood waste.

Improved drying techniques: Solar drying utilizes solar energy for wood drying, reducing reliance on fossil fuels and lowering energy consumption and carbon emissions. Microwave drying uses microwave technology for quick and uniform heating, shortening drying times, reducing energy consumption, and avoiding deformation caused by uneven drying.

Wood protection treatments: Eco–friendly preservatives such as borates and preservative oils replace toxic chemical preservatives, reducing harm to the environment and human health. Thermal treatment improves the durability and resistance of wood without the need for chemical agents.

2.1.2.2 Pulp and paper

Chlorine-free bleaching technologies: Chlorine–free elemental bleaching employs non–chlorine elements instead of traditional chlorine elements to reduce dioxin and other toxic substance emissions [30]. Total chlorine–free bleaching uses ozone, oxygen, hydrogen peroxide, and other non–chlorine chemicals for pulp bleaching, completely avoiding chlorinated compound emissions, making it more environmentally friendly.

Closed-loop water circulation systems: In the paper making process, closed–loop water circulation systems recycle waste water after multistage treatment for reuse in production and reduce fresh water usage and wastewater discharge. Advanced water treatment technologies such as membrane filtration, reverse osmosis, and biological treatment improve waste water treatment efficiency and ensure that the effluent meets environmental standards.

Biomass energy utilization: Waste–to–energy converts wood chips, bark, and paper sludge from paper making processes into fuel for power generation, reducing dependence on fossil fuels. Biofuels transform paper making waste into biofuels such as ethanol and methane for use in boilers and power equipment, lowering carbon emissions.

Mechanical pulping: High–efficiency mechanical pulping technologies, such as double–disk refiners and disk refiners, improve pulp production efficiency, reduce energy consumption, and lower chemical usage. Cold pulping utilizes low–temperature processes to minimize wood fiber damage, improve pulp quality, and reduce energy consumption and pollutant emissions.

2.1.2.3 Wood-based composite materials

Eco-friendly adhesives: Bio–based adhesives made from natural materials like soy protein, starch, and resins replace formaldehyde–containing adhesives, reducing emissions and use of harmful substances [31]. Water–based adhesives decrease the use of organic solvents, lowering volatile organic compound emissions and benefiting the environment and human health.

Waste reuse: Recycled wood–plastic composites mix waste wood and plastic scraps to create wood–plastic composite materials, utilizing waste resources while possessing good mechanical properties and weather resistance. Recycled paper fiber boards use waste paper fibers to produce fiberboard materials like hardboard and sound insulation boards, achieving efficient use of waste paper resources.

2.1.2.4 Advanced manufacturing technologies

2.1.2.4.1 Digital manufacturing

Computer-aided design (CAD): Employing CAD technologies to control the woodworking process precisely, thereby minimizing material waste and enhancing production efficiency [32].

3Dprinting: Utilizing 3D printing techniques for the fabrication and processing of wood and wood–based materials, facilitating customized production and the efficient creation of complex structures.

2.1.2.4.2 Lean production

Reduction of scrap: Adopting lean production philosophies to optimize production workflows and minimizing scrap generation at every stage, resulting in improved resource utilization.

Energy efficiency: Implementing energy–efficient equipment and processes, such as high–efficiency motors, energy–saving lighting fixtures, and intelligent control systems, to decrease energy consumption during the production process.

2.1.3 Product lifecycle management

Conduct lifecycle assessment (LCA): Assess environmental impacts a teach stage from raw material acquisition, production, use, to disposal, ensuring minimal environmental load at every step.

Design optimization: Consider disassembly, recyclability, and reuse in product design, extending product life and reducing waste generation.

Waste management: Develop postconsumer recycling and reuse schemes to minimize environmental pollution and resource waste.

2.1.4 Social and economic sustainability

Sustainable/Circular forest products not only focus on environmental protection but also emphasize social and economic sustainability.

Fair trade: Ensure fairness in the forest product trade, protecting the rights of producers and workers.

Community development: Promote local community development and economic prosperity through the production and sale of forest products.

Market promotion: Increase consumer awareness and recognition of sustainable forest products through green certification and marketing, stimulating market demand for sustainable products.

2.2 Concept and theory of circular forest products (CFP)

2.2.1 Concept of CFP

A circular/sustainable/green forest product represents an economic–environmental–lifestyle model supported by technology. It involves planning, designing, coordinating, and managing the cultivation, utilization, production, reprocessing, consumption, and recycling of resources throughout the product life cycle to maximize resource ecosystem functions and human well-being. It uses lifecycle analysis

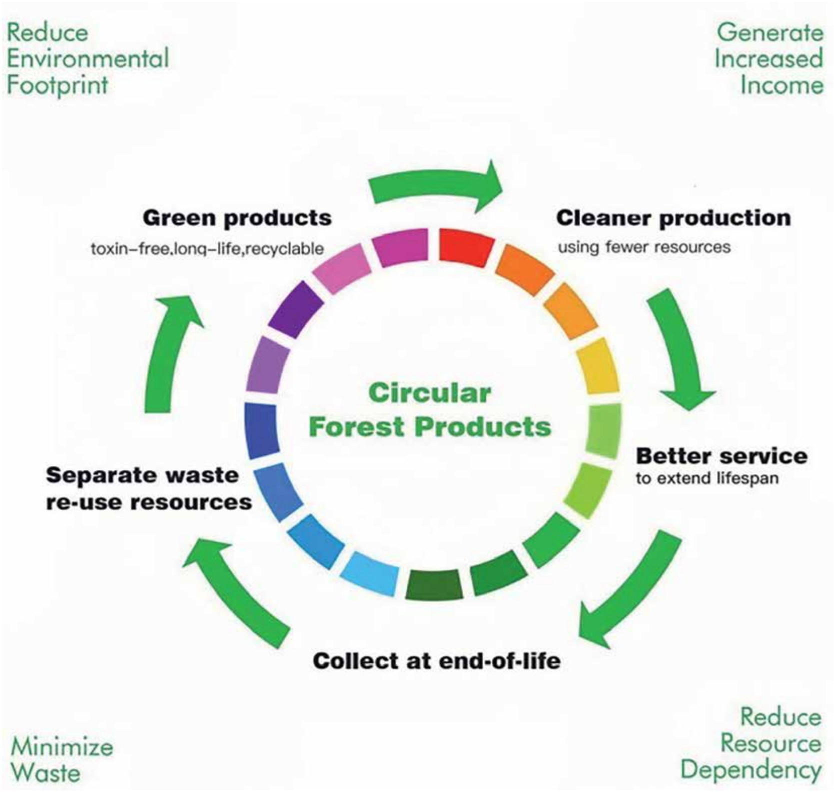

Figure 1.
Circular forest products concept.

as an assessment method. Philosophically, it embodies the principle of nature: all things arise and disappear interdependently, and everything optimally or most efficiently utilizes raw materials, consumes the least energy, and produces no waste or residues (**Figure 1**).

2.2.2 Basic principles of CFP/economy

The CFP is a part of the circular economy. It is a product reflecting the traditional linear economic model ("extract–produce–consume–dispose"). It emphasizes achieving the maximization of resource utilization and minimization of environmental impact through the "reduce–reuse–recycle" approach. The theory and conceptual framework of the CFP are based on this foundation (**Figure 2**).

Generally, CFP can be described as a method to reduce the consumption of forestry resources by closing the cycles of forestry resources [33]. Borrowing from the Ellen MacArthur Foundation's definition of the circular economy, it can be defined as "an industrial economy designed and planned for deconstruction and regeneration" [34, 35], aiming to "gradually decouple economic activity from the consumption of finite resources." Based on the definition of the circular economy, three principles of CFP can be proposed: eliminating waste and pollution through design/planning, ensuring the efficient use of products and materials, and regenerating forest ecosystems.

According to another definition of the circular economy proposed by the European Commission, the CFP can also be defined as a process that "keeps the value of products, materials, and forestry resources in the economy for as long as possible and minimizes waste generation throughout the entire product lifecycle" [36].

This may show that a unified definition of CFP is necessary. Additionally, as a mode or policy, the implementation of CFP should be equipped with an assessment method. That is, the definition of CFP should automatically provide an evaluation method.

Although there are different interpretations of CFP, it should be pointed out that the CFP model is built on responsible and circular use of forestry resources and strives to minimize waste and pollution generation [37]. Therefore, a key indicator of whether a production system or economic model is circular or sustainable is whether the materials in the system are reused.

2.2.3 Key elements of CFP

- Establish a renewable forest resource system.

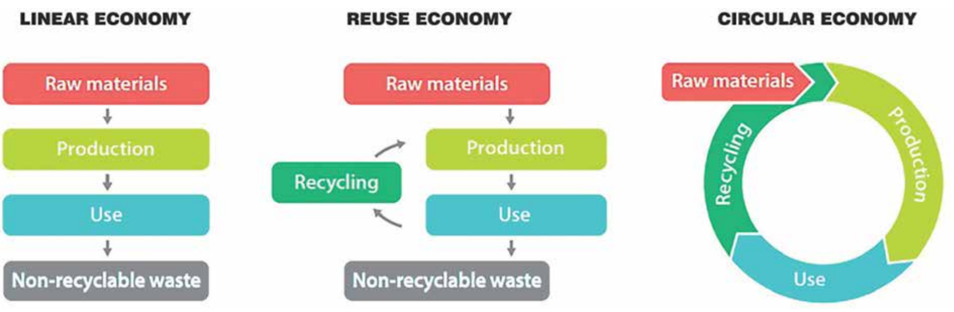

Figure 2.
Illustration of different economic concepts (from FAO).

- Raw material preparation: Select and procure sustainably produced materials with minimal environmental impact.

- Planning and design: Prioritize material use efficiency, durability, and recyclability in product formulations, processing methods, and procedures.

- Coordination and management: Establish systems for optimizing resource allocation, production scheduling, and waste management.

- Resource procurement: Source materials and energy from green, sustainable origins, considering factors such as material origin, transportation, and environ–mental impact.

- Production: Implement manufacturing processes that minimize raw material waste, waste emissions, and energy consumption.

- Post treatment: Recycle waste into reusable resources or new products.

- Consumption: Encourage responsible consumption patterns among consumers and government structures, promoting product repair, reuse, and recycling of raw materials.

- Recycling: Recover and reuse materials from products at the end of their first lifecycle, designing recyclable products to prevent premature disposal in landfills or incineration. Ensure that residual materials from landfills or incinerators can be utilized in forestry, completing the cycle from forest products back to forestry (**Figure 3**).

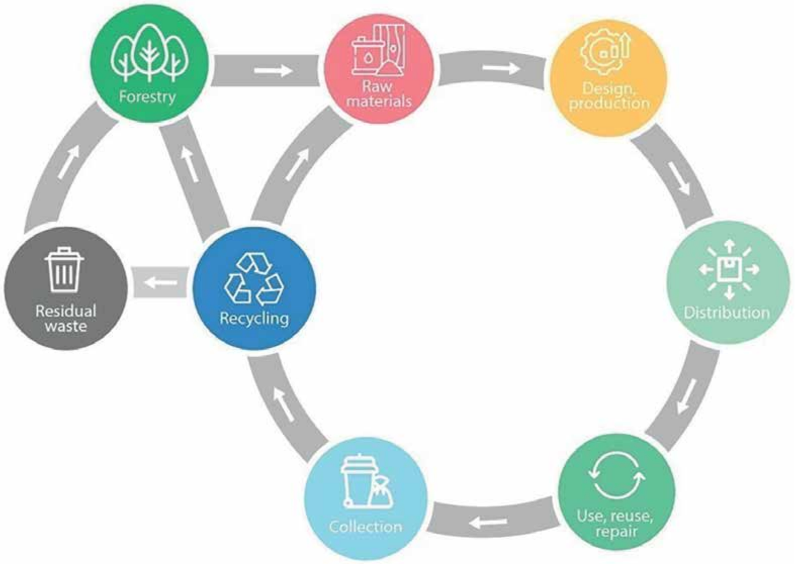

Figure 3.
Key components of the CFP concept (adopted from FAO).

2.2.4 Implementation pathways for CFP

2.2.4.1 Technological innovation

New material development: Develop renewable and eco–friendly materials to enhance recycling rates.

Improvement of manufacturing processes: Enhance efficiency and product quality by refining production methods.

New products design: Widen product choices with materials available *via* no waste principle.

2.2.4.2 Circular business models

Circular business models redefine the relationship between consumers and products, considering the limitations on forest resource availability and their impact on the production and consumption of new goods. These models encourage obtaining goods through leasing and sharing rather than purchasing and owning them, especially when considering the scarcity of forest resources.

Similar to circular business models outlined [38], the operational model for CFP could include:

Circular supply model: This emphasizes replacing traditional nonrenewable, non–biological, high–energy–consuming, and non recyclable materials with renewable, bio–based, low–carbon, and recyclable inputs. By utilizing renewable forest resource systems and cradle–to–cradle product design, it aim stoclose material loops, generating nutrientsforregenerativeforestresourcesystemswhileminimizingwasteemissions.

Resource recovery model: This business model focuses on producing secondary raw materials from waste streams. Waste is collected, sorted into its constituent materials, and then transformed back into raw materials, creating closed material loops.

Variations include recycling, upcycling, and industrial symbiosis, where one company's waste becomes another company's input.

Product life extension model: This model seeks to extend product lifespans and retain products and materials for as long as possible, prolonging material usage. It involves designing high–quality, long–life cycle products, direct reuse, maintenance, repair, refurbishment, and remanufacturing.

Sharing model: This model aims to increase the utilization rate of existing products, equipment, and resources. Underutilized consumer assets are more intensively used. Through co–ownership and co–use. Online platforms reduce transaction costs and related risks. Transactions typically occur between consumers temporarily rather than permanently, seeking concentrated asset utilization rather than service provision.

Product-service system model: This combines physical products with service components to promote resource circulation. Consumers purchase the services provided by the product while producers retain ownership. This model is particularly applicable to companies producing high–value products like forest management services, wood leasing and recycling, packaging material recycling services, biomass energy services, customized wood products, carbon sink trading services, and ecotourism services.

2.2.4.3 Policy and regulation

The concept and theory of CFP development are still in their infancy, and their implementation requires government policy support. Governments should incentivize forest industry enterprises to adopt CFP models through relevant policies and regulations, for instance, by providing tax incentives and subsidies to support green, circular, and sustainable production and technological innovation while establishing an implementation system for CFP.

Additionally, specialized standards, certification, and evaluation systems for CFP should be established: developing and promoting standards and certification systems for CFP to enhance market recognition and acceptance; strengthening education and research on CFP to rapidly complete the cycle from forest products to forestry.

3. Green, sustainable theory foundation for CFP

3.1 Relationship between circular economy and CFP

There is a close relationship between the circular economy and CFP. Like the circular economy, the concept of CFP aims to drive the forest industry in a more sustainable direction by reducing forest resource consumption, improving resource efficiency, and minimizing waste generation.

Both definitions of them focus on material efficiency and system impacts, adhering to three guiding principles: Reduce (minimum use of raw materials), Reuse (most efficient use of products and components), and Recycle (high–quality reuse of raw materials). This is also known as the three Rs or 3R principle of sustainability [39].

The 3R principle partly reflects the reuse economy (**Figure 2**). It is important to note that in the closed–loop system of CFP, what matters is not just the proper recycling of materials but also ensuring that products and raw materials maintain sufficient quality for reuse. This can be seen as a combination of the 3Rs and a systematic approach, extending the focus to material use and its impact on the system [40].

Naturally, for CFP, the emphasis is often on how to cascade the use of woody materials, meaning making full use of by products from the production process.

3.2 Key theories and evaluation tools

3.2.1 Theory of circular economy (CE)

The theoretical foundation for CFP is the CE theory, which is an economic model aimed at reducing waste emissions and environmental impacts through the continuous reuse, recycling, and circulation of resources. Unlike the traditional linear economy (“take–make–dispose”) model, the CE pursues a closed–loop flow of resources to achieve a win–win scenario for both the economy and the environment.

Although there is no universal consensus on the definition of CE, some definitions are used more frequently than others. For example, the definition proposed by the Ellen MacArthur Foundation describes the CE from the perspective of material use and systems, focusing on the design of materials, products, and systems. It draws on the principles of Cradle to Cradle and systems thinking [41]. Its fundamental premise is that the circularity of products is considered at every stage of their lifecycle, from conception to design and development, then through use, disposal, and reuse [42].

The European Environment Agency states that the concept of circularity can be applied to various natural resources, including biotic and abiotic materials, water, and land. “Ecological design, repair, reuse, refurbishment, remanufacturing, prevention of waste generation, and waste recovery are all important in a circular economy” [43].

However, it is noteworthy that the EU–level approach to the CE primarily focuses on achieving circularity through resource efficiency and technological change.

3.2.1.1 Life cycle assessment (LCA)

LCA is a method for calculating the carbon footprint of a product or service throughout its entire lifecycle. The entire lifecycle calculation spans from “cradle to grave”: from raw material extraction to production, packaging, use, disposal, recycling, and final disposal. It is a systematic analysis method for evaluating the environ–mental impact of a product over its entire lifecycle. The main steps of LCA include:

Definition of objectives and scope: Clearly define the purpose, scope, and boundary conditions and determine information requirements, data specificity, collection methods, and data representation together.

Inventory analysis: Collect and quantify data on resource consumption and pollution emissions at each stage of the lifecycle of products.

Impact assessment: Analyze and evaluate the specific environmental impacts of these data, such as greenhouse gas emissions, resource depletion, water pollution, etc.

Interpretation and improvement: Based on the assessment results, propose improvement measures to optimize product design and production processes.

4. Case studies on green/sustainable/circular development

4.1 Case study 1: Bavarian forest (Germany)

In Germany’s Bavarian Forest, a new approach to carbon accounting models highlights the critical role of the sustainable cascading use of wood in carbon reduction strategies [44]. By clearly distinguishing between the relationship of carbon fluxes and carbon pools, as well as carbon fluxes and the atmosphere, it demonstrates the explicit contribution of sustainably produced forest products to carbon reduction policies. Through this new carbon accounting model, issues regarding how to better consider the carbon stored in wood products within existing carbon models are addressed, thereby providing more accurate guidance for carbon reduction strategies and alternative suggestions to address threats like climate change, taking into account ecological, social, and economic aspects to explore the need for sustainable forest management.

4.2 Case study 2: Pulp and paper industry (Canada)

Canada’s pulp and paper industry employs advanced waste water treatment technologies and energy recovery systems, effectively reducing pollutant emissions during pulp and paper production [45]. Moreover, the large–scale recycling of waste paper has significantly reduced the demand for virgin wood in the pulp and paper industry. Specific measures include:

Wastewater treatment: Advanced waste water treatment technologies, such as biological degradation and physical filtration, are introduced, significantly reducing pollutant emissions.

Energy recovery: Many paper mills have installed energy recovery systems, generating steam and electricity by burning waste paper pulp and residues from pulp and paper production, achieving self–sufficiency in energy supply.

Circular utilization: Large–scale promotion of waste paper recycling technology, increasing the recycling rate of waste paper and reducing the demand for virgin wood in pulp and paper production.

Sustainable certification: Many Canadian forest product companies have obtained Forest Stewardship Council (FSC) or the Program for the Endorsement of Forest Certification (PEFC) certification, ensuring that their products meet sustainable development standards during production.

4.3 Case study 3: Biomass energy projects (Sweden)

Sweden is a leading country in the utilization of biomass energy. It promotes the green development of the forest industry by producing biomass energy from forestry residues [46]. Specific measures include:

Raw material utilization: Forestry residues such as branches, bark, and sawdust are used as raw materials for biomass energy, avoiding resource waste.

Energy production: Biomass power plants are constructed to convert biomass into electricity and heat, providing energy for local communities and industries.

Greenhouse gas reduction: By substituting fossil fuels, significant reductions in green house gas emissions are achieved, driving the development of a low–carbon economy.

Policy support: The Swedish government provides financial subsidies and tax incentives to encourage the development of biomass energy projects.

4.4 Case study 4: Revival of wood architecture (Japan)

Japan has made significant progress in modern wood architecture, promoting the green utilization of wood [47]. Specific measures include:

Modern wood architecture technology: Technologies such as cross–laminated timber (CLT) and glued laminated timber (Glulam) are adopted to improve the strength and durability of wood architecture.

Policy promotion: The government enacts policies to encourage the use of wood in public building construction and offers tax incentives and loan support for wood architecture.

Environmental benefits: The vigorous development of wood architecture technology reduces carbon emissions in the manufacturing process compared to steel–rein–forced concrete buildings, while clarifying that wood can store carbon during use.

Cultural promotion: Japan enhances public acceptance and awareness of wood architecture through publicity and education, promoting the revival of wood in the architectural field.

Indeed, above cases illustrate successful practices in green, sustainable, and circular development from various countries and regions, spanning multiple domains including forest management, industrial production, energy utilization, and architectural design. Through the implementation of innovative technologies and policies, these examples demonstrate the feasibility and significance of sustainable development on economic, social, and environmental fronts.

5. Overview of China's forest industry status

The 26th Conference of the Parties to the United Nations Framework Convention on Climate Change was held in Glasgow, UK. Leaders of over 100 countries, including the U.S., China, the UK, and Russia, pledged to halt and reverse deforestation and land degradation trends by 2030.Thiswill require a global consideration of how to utilize forest resources more effectively from the perspective of circular forest products.

For decades, Chinese planted forest area has been continuously expanding, reaching over 80 million hectares in 2022, ranking first in the world. China meets approximately 60% of the global demand for plywood, using less than 5% of the world's forestry resources. This indicates that Chinese forestry and forest industry development is sustainable; the utilization of forestry resources there is relatively efficient on a global scale.

In recent years, thanks to the rapid increase in the production capacity of the timber industry and significant labor cost advantages, China's forest product trade has continuously expanded in scale. In terms of exports, forest products such as wood–based panels, furniture, paperboard, and paper products rank among the top globally.

China has developed into a world–leading processing hub and trading power for forest products [2]. China's rapid economic progress and the aforementioned international situation have led China to place greater emphasis on green, sustainable, and circular development.

In the process of actively leading and participating in peaceful globalization development, China accepts challenges, develops, and creates new universal values, innovating China's political, economic, cultural, and industrial development systems, especially in green, low–carbon product manufacturing standards and policies, to lead the sustainable development of the global forest products industry:

Green standard system construction: China has initiated the construction of a standardized work system for a green, low–carbon, and circular development economy, including standards for green manufacturing, green products, factories, enterprises, parks, supply chains, and evaluations and services. The "General Criteria for Green Factory Evaluation" (GB/T 36132–2018) and other national standards have been formulated, establishing a green factory system evaluation index system.

Forestry industry standards construction: Over the years, China's National Forestry and Grassland Administration has released 51 forestry industry standards, mainly involving seedling cultivation and planting, forestry carbon sink measurement and monitoring, land classification, forest resource survey technical specifications, desertification and stone desertification monitoring technical specifications, protection of extremely small populations of wild plants, wild life breeding, forest specialty products, plant new varieties, and forest product production. On October 1, 2021, China officially implemented the standard GB/T 39600–2021 "Formaldehyde Release Grading of Wood–based Panels and Their Products."

Green product evaluation standard system construction: China is actively promoting the construction and revision of a green product evaluation standard system.

Through the formulation of the "General Criteria for Green Product Evaluation" (GB/T 33761–2017), China has stipulated the basic principles, evaluation indicators, and evaluation methods for green product evaluation, providing a basis for the formulation of specific green product evaluation national standards.

These efforts show that China has not only made progress in its own development in sustainable development, but also offered new perspectives for the sustainable development of the global forest products industry.

Undoubtedly, there are many differences between China's forest products industry and the international forest products industry:

5.1 Raw materials

China is a country with scarce forest resources based on her population, severely lacking in timber supply, and highly dependent on exogenous raw materials supply. On one hand, China's large imports of timber have drawn criticism from some international organizations. On the other hand, the fact that China uses 5% of the world's forest area and 3% of forest reserves to support the growing timber consumption needs of 20% of the world's population and China's increasingly efficient utilization of global forest resources in its forest industry are increasingly recognized by the international community. This requires China to draw on its own development experience, collaborate with other countries, and create a sustainable CFP theory to help the global development of the forest and forest products industry.

In China, the forest and forest products industry is also a labor–intensive industry.

The development of the industry not only involves the country's economic development but also relates to the employment of millions of citizens. Taking the wooden furniture industry as an example, which is most closely related to timber raw materials, there are approximately 20,000 wooden furniture manufacturing enterprises in China, employing nearly2 million people. Including indirect employees and family members, there are nearly 10 million stakeholders in furniture production.

Therefore, according to the theory of CFP, the application and processing of furniture raw materials should be redesigned to fully demonstrate and better utilize the inherent biological characteristics of different raw materials. On the other hand, the completion of the circulation/circle from CFP to resources should be expedited to ensure the sustainable development of forest resources and assist the industry in producing higher–quality timber/wood resources to ensure the sustainable development of the industry.

5.2 Challenges faced

The Chinese forest products industry is an industry that completes the production of various forest products through certain processing processes using wood and nonwood materials. To summarize the overall developmental trend of the industry, the urgent problems that need to be solved in the industry include:

Low-carbon transformation of China's forest industry: After years of effort, China implemented the GB/T 39600–2021 "Grading of Formaldehyde Release from Wood–based Panels and Their Products" standard on October 1, 2021. The Emission non formaldehyde (ENF) level formaldehyde emission in the standard not only far exceeds the formaldehyde release requirements for current F–OSB/2 type panels but also surpasses those specified by Japan and the European Union [48]. The implementation of the ENF level formaldehyde emission standard ensures consumers with more environmentally friendly and healthy home choices while promoting the development of related industries, encouraging the research and development, and production of green building materials. Despite this, the establishment of ISO series standards aimed at controlling and reducing carbon dioxide emissions, China's "Dual Carbon" targets, the Composite Panel Association's proposal of the Eco–Certified.

Composite certification program for wood–based panels, and the realization of sustainable certification for wood–based panels such as particle board and medium–density fiberboard globally require the forest product industry to promptly improve its low–carbon wood–based panel industry standards, accelerate the establishment of a low–carbon industrial system, and complete tasks characterized by low emissions, low pollution, and recyclability for the sustainable development of the global forest products industry.

Lack of robust theoretical support: This will lead to lagging technological innovation efforts, increased risk of decision–making errors, low resource utilization efficiency, exacerbated environmental problems, weak market adaptability, inadequate education and talent cultivation, and declining international competitiveness. To overcome the issue, it is necessary to strengthen theoretical research in the field of the forest and forest products industry, especially comprehensive research on the theory development of CFP, including the exploration of forest ecosystem establishment, wood science and technology, forest product markets, environmental impact, sustainable and circular development strategies, etc. This requires close cooperation between government, industry, academia, and research institutes.

Unclear understanding of the concept of CFP: Although the concept of CFP has been proposed for many years, the development goals of the industry are not precise, and basic concepts are ambiguous. Theoretical issues in the development of forest products, such as "What are circular forest products? What is a low–carbon sustainable economy? How to develop CFP?" remain unresolved. The industry requires strong theoretical guidance, and fundamental research topics for CFP must be conducted and resolved as soon as possible. This has also resulted in an incomplete CFP system in China, lack of a logic complete industrial chain and its design in the forest industry development, and absence of clear direction for the forest products industry development. Therefore, a consensus on the definition of CFP should be reached, and the construction of the entire industrial chain should be completed under the guidance of the CFP theory.

The practical implementation of the CFP concept should be pursued diligently, while we actively seek governmental support to offer perspectives for the sustainable development of society as a whole.

6. Outlook for the forest product industry

6.1 Global trends

Looking at global trends, due to the influence of human "ecological awakening," renewable and pollution–free wood and its products, as well as other forest products, are increasingly favored. Meanwhile, governments worldwide, considering the long–term benefits of sustainable development, are setting aside large areas of social welfare forests and strictly enforcing logging bans [49]. While global forest product trade continues to grow, structural contradictions in supply and demand persist, and there remains an imbalance in CFP trade between regions and countries. With the sustained global economic development, global demand for forest products will continue to grow, but the growth trend will slow down.

The proportion of high–value–added forest products will increase significantly. As global economic integration deepens, large multinational corporations in developed countries are transferring labor–intensive industries, and even capital and technology–intensive industries and high–tech industries, to developing countries to lower production costs and enhance competitiveness. Asia, particularly China, is gradually becoming a new center for global forest product processing and trade [50]. Currently, the future global trends for CFP mainly include the following aspects:

Regarding the log market, projections by FAO indicate that although global industrial round wood supplies may grow, the growth rate will be significantly lower. This is due to an increasing number of countries protecting natural forests, implementing sustainable development strategies, restricting and banning log exports, as well as the limited production capacity of countries capable of supplying substantial volumes of temperate timber to the international market, excluding Russia. Countries such as New Zealand, Chile, and South Africa produce timber from plantations, each with limited production capacity.

Regarding plantation timber supply, it is expected that large–scale commercial short–rotation plantations in the southern hemisphere will begin operations in the next decade or so. It is anticipated that the proportion of plantation timber in increasing timber production will gradually rise.

Regarding forest product production, consumption, and trade, developed countries will not only continue to dominate industrial round wood, wood–based panels, and paper product production and consumption but also remain dominant in forest product trade, particularly in high–value–added products. Some wood–deficient countries, such as China, Japan, South Korea, the UK, and Italy, will continue to rely on the international market to meet domestic forest product demands.

6.2 Technological innovation

In the development of forest resources, improving resource utilization efficiency, reducing resource consumption, and upgrading through technological innovation and industrial transformation to enhance the processing level of wood and other forest products, increasing product added value, and achieving efficient resource utilization is a trend [51]. Innovation in sustainable CFP originates from efforts in new product development and continuous incremental improvements to existing products. Process innovation refers to refining manufacturing processes, typically to improve yield and conversion efficiency, ultimately aiming to reduce costs. Lastly, business system innovation involves improvements in how companies manage their business operations. Cross–industry research consistently shows that the development of new forest products is crucial for long–term competitiveness. Companies in the forest products industry with more structured new product development processes tend to be more successful in bringing new products to market [52].

6.3 Policy and market drivers

The development of the forest products industry cannot be separated from the impetus of policy and market forces. Countries formulate trade policies for various purposes, including expanding the market for domestic products, broadening sources of capital and funds, protecting domestic resources and the environment, and ultimately contributing to the overall goal of development. From an external perspective, countries participate in bilateral or multilateral trade agreements to satisfy diplomatic and political needs. Studying the main forest product trade policies adopted by various countries, grasping their development directions, and tracking their development priorities and trends are of significant importance for China to formulate its own forest product development policies and better respond to changes in this international communication [53].

6.4 Development recommendations based on CFP theory

Based on the definition of CFP, the general recommendations to the forest products industryarethattheforestproductsindustryneedsreorganizingtobuild a complete forest product industry chain to ensure the industry is circular and sustainable *via* cloud data/AI platform. Forest products research and education should work in the direction of circular and sustainable to ensure the forest products developed at the end can be used in sustainable forestry resource development, and society should develop more CFP markets and have more specialists in the CFP area. More specifically, *From the perspective of resource cultivation*: After the lifecycle of CFP is completed, ensure that these forest products can contribute to the sustainable development of forest resources.

From the perspective of resource utilization: Clearly specify that only plantations intended for forest product production should be used, and propose requirements for tree planting schemes, regions, and soil chemistry from the perspective of effective utilization of forest product resources.

From the perspective of production processes and products: On one hand, the waste from the production process of one product should be designed to become a high– quality raw material for the production process of the next product to ensure that each production process can produce the best quality product with the least amount of energy. On the other hand, products or production processes should be designed to fully utilize waste from other industries to enhance or increase the properties or performance of forest products, ensuring that society as a whole can reduce the energy required to recycle these wastes. Furthermore, products should be designed to enhance their recyclability.

From the perspective of ecological services: In the field of wood architecture, more research should be conducted to tap into the ecological functions of trees, encouraging people to use this sustainable material and providing information.

In the domain of recycling and circularity research, it is imperative to develop appropriate recycling processes that reduce energy consumption during the recycling of forest products, enhance the benefits of recycling, and motivate society at large to engage in recycling activities more enthusiastically.

Within the realms of product sales and market development, it is suggested to forge alliances between furniture manufacturing and sales companies and forest product manufacturers. This collaboration should aim to promote recycling and foster brands that are both recyclable and sustainable.

Drawing inspiration from invasive species, one should advocate for the northward utilization of southern–origin materials in product usage. This strategy circumvents the natural enemies of wood materials, decreases material usage costs, and prolongs product lifespans.

In the sphere of product consumption and usage, concerted efforts should be made alongside product after–sales service companies to educate customers on proper usage and care for products. Concurrently, these service companies should assist customers in identifying top–tier brands, extending product service cycles, and nurturing a market and customer base imbued with the philosophy of CFP.

Regarding the formulation of corporate sustainability policies in the forest industry, including product development and employee recruitment, there should be a clear articulation of the mission and confidence in the sustainable development of the forest industry. It is essential to unify the development philosophy of the forest industry, streamline promotional strategies, and solidify developmental theories.

The success or failure of all forest product development measures ought to be evaluated through life cycle analysis, ensuring a holistic understanding of their environmental impact and sustainability.

In the context of sustainable development policies for the forest products industry, it should be unequivocally stated that only the sustainable development of the forest industry can genuinely secure the sustainability of forestry development. The design of forest products should anticipate their eventual utility in forest growth, thereby establishing a cycle from forest products back to forestry. This ensures that forest products can ultimately contribute to the enhancement of green mountains and waters. Simultaneously, there should be a profound acknowledgment of the hardships involved in realizing the concept of CFP and the limitations of market economics.

7. Conclusions

This paper comprehensively explored the theoretical foundations of green, sustainable, and recycled forest products, global practice cases, and the current situation and challenges of the Chinese forest and forest product industry. It emphasizes the importance of the forest products industry in promoting economic development, environmental protection, and social progress. The global forest products market is moving toward diversification while facing challenges such as over–exploitation of resources, the impact of climate change, and trade friction. Successful national practices in a variety of areas, including forest management, industrial production, energy use, and building design, have shown that the green, sustainable, and circular development of forest products can be effectively realized through innovative technologies and policy support. Looking to the future, the forest products industry needs to strengthen technological innovation, improve resource utilization efficiency, and enhance the added value of products. Policy and market–driven will be the key factors to promote the development of the industry. Based on the theory of CFP, this paper suggests that the industry should be reorganized to build a complete industrial chain and use cloud data and artificial intelligence platforms to ensure the circularity and sustainability of the industry. At the same time, the circular and sustainability orientation of forest products research and education should be strengthened, more experts in the field of CFP should be cultivated, and the CFP market should be developed. In addition, this paper calls for industry–wide joint efforts to clarify the development direction of the forest products industry, improve the theory of CFP, establish a standardized assessment system, and promote green and low–carbon production and consumption patterns across the industry to make a greater contributions to global ecological environmental protection and economic and social development.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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