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Thermal Modification of Wood: Mechanisms, Property Changes, and Industrial Applications – A Review

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Annotation: Heat treatments to modify wood have become an effective and green methodology of improving wood functionality without use of chemical preservatives. When timber is exposed to high temperatures under harshly regulated circumstances, some significant changes in the chemical and structural characteristics of cell wall polymers take place, leading to enhanced dimensional stability, reduced hygroscopicity, and increased biological longevity. The review summarises the principles, processes and mechanisms involved in thermal modification of wood, specifically the degradation of hemicellulose, alteration of cellulose crystallinity, condensation of lignin and the resulting degradation of hydroxyl functionalities.

The effects of thermal modification on of physical and mechanical properties of wood are critically analysed and the effects include variations in density, moisture sorption kinetics, dimensional stability, colouration, thermal conductivity, and strength properties. Although timber treated using thermal treatment shows a high level of resistance to moisture ingress and biological decay, diminished mechanical strength and a higher level of brittleness have been identified as the main limitations thus limiting its use to non-structural cases mostly. The review also outlines the current industrial thermal modification technologies and outlines modern and future uses of thermally modified wood as an exterior and interior product, including cladding, decking, flooring, and furniture.

Lastly, the article appraises the benefits and shortcomings of thermal modification in comparison to traditional forms of chemical and mechanical wood modification procedures, and suggests the future research directions intended towards optimising treatment regimes, retaining the strengths properties and enhancing the overall sustainability profile of thermally modified wood products. This literature review leads to the sophisticated perception of thermal modification as the key technology of sustainable use of timber resources.

Keywords: Heat-treated wood; Wood characteristics; Dimensional stability; Biological resistance; Sustainable wood material.

Introduction

Wood is a versatile renewable natural resource and a central part of the construction, furniture, and many other industrial applications. Its good mechanical behaviour, low density, aesthetic nature and environmental qualities make it an appealing substitute to non-renewable materials. However, regardless of these benefits, the use of untreated wood is often limited by inherent factors, such as extreme hygroscopicity, dimensional volatility and exposure to biological decay by insects and fungi (Hill, 2006; Siau, 1995). These limitations significantly reduce the durability of wood products especially in open air and humid conditions.

The hygroscopic behaviour of untreated wood is one of the most severe failures, and the origin of the latter can be traced to the concentration of hydroxyl groups in cell wall polymers, especially hemicelluloses. It is a property that causes constant absorption and desorption of moisture with changes in ambient humidity leading to swelling and shrinkage. The surface cracking, warping and structural integrity loss are possible during the service due to dimensional variations (Siau, 1995). Besides, untreated wood provides a favourable environment to biological organisms, including fungi of decay, termites, and insects that can easily destroy the material in the presence of favourable climatic conditions (Schmidt, 2006).

Different preservation methods and wood modification have been invented to overcome such disadvantages. The traditional chemical methods have proved to be useful at improving the durability, but increased environmental and health apprehensions about toxic preservatives have resulted in the search of alternative, environmentally harmless solutions (Hill, 2006). In this context, thermal modification of wood has gained more attention as a natural and non-chemical way of modification.

Thermal modification involves subjecting wood to a high temperature of the range 160 0 C to 260 0 C under controlled conditions including inert gas, steam, or oil, and no bio-killing chemicals are added. As a result of this process, the chemical composition and microstructure of wood undergo modification which results in lower hygroscopicity, better dimensional stability, and resistance to biological degradation (Esteves & Pereira, 2009; Militz, 2002). The thermal modification is also more permanent because the substances are added to the wood, unlike the traditional process of preservation, which adds external elements that are poisonous.

Scientific study of the heat-treated wood can be traced back to the middle of the twentieth century. Early experiments had shown that heating wood could strongly decrease the moisture sorption capacity of that material and enhance decay resistance; nevertheless, there were early methods that produced significant degradation of mechanical qualities by thermal destruction that remained uncontrolled (Stamm, 1956). Further studies were directed towards the understanding of thermal behaviour of wood polymers and the optimum treatment conditions to ensure the ease of achieving enhanced durability and moderate mechanical performance.

Innovations in process control and wood chemistry resulted in the emergence of contemporary industrial thermal modification technologies at the end of the twentieth and the beginning of the twenty-first centuries. A number of the commercial processes have been effectively deployed, especially in Europe. In Finland, ThermoWood process is one of the most popular technologies in the world, using steam as a protective media during heat treatment, and is developed and implemented (International ThermoWood Association, 2021). Plato is another interesting process that combines the steps of hydrothermal treatment and curing, as well as retification processes, which are based on the high-temperature treatment in an oxygen-free environment (Militz and Altgen, 2014). Such technologies have enabled mass productions of thermally modified wood which can be used in exterior and interior purposes.

The processes involved in the thermal modification are mostly related to the chemical modification in the cell wall of wood. The least thermally resilient constituents (hemicelluloses) degrade to cause a decrease in accessible hydroxyl groups and resultant decrease in moisture sorption (Esteves and Pereira, 2009). At the same time, lignin undergoes condensation and cross-linking reactions which enhance the hydrophobicity and biological resistance (Tjeerdsma & Militz, 2005). These are the chemical changes which are accompanied by the microstructural changes which in combination affect the physical, mechanical and durability of thermally modified wood.

Even though it has its benefits, thermal modification does not lack limitations. Mass loss and structural polymers can be degraded as a result of elevated treatment temperatures leading to the loss of mechanical ability and increase in brittleness especially in bending and impact resistance (Boonstra et al., 2007). Thermally modified wood therefore is mostly suggested to be utilized in non-structural applications where structural integrity and stability are more important than strength.

With the increasing demand of sustainable materials and environmentally friendly technologies, thermal modification has become one of the key spheres of study and industrial activity. Its effects on wood chemistry, physical and mechanical behaviour, durability and environmental performance have been studied by many researchers. Nevertheless, the available literature is very large and diffused in different fields, making a synthesis very necessary. Recent systematic reviews highlighted the need to understand modern trends and future challenges in heterogeneous developmental sectors in a holistic analytical approach, by focusing on the interplay between structural conditions and economic determinants and long-term planning (Palani, 2025a; Palani, 2025b).

This review article aims at critically assessing the present status of knowledge in thermal modification of wood. The review aims at the basic processes of thermal modification, resultant alterations in the wood properties and implications on industrial uses. Besides, the environmental factors, limitations, and future research perspectives are also talked about. Through both experimental results and industrial application, the review seeks to give a consistent and modern picture of a thermal modification as one of the technologies that may be used in the sustainable use of wood.

Essentials of Thermal Modification of Wood.

Controlled, wood is subjected to high temperatures and placed under various environmental conditions to thermally modify its chemical composition and physical structure to result in permanent changes in the selected performance properties, including dimensional stability, moisture resistance, and biological durability. Thermal modification is a preservation technique that differs with conventional ones since it does not pit the use of toxic chemicals but rather it alters the inherent characteristics of wood as a result of heat induced chemical reactions (Hill, 2006; Esteves & Pereira, 2009).

Conceptually, the thermal modification can be referred to as a non-chemical approach to modifying wood whereby modification of the wood mainly occurs at the polymers that constitute the cell-wall. The process influences the relative proportions and structures of cellulose, hemicelluloses, and lignin, which leads to a decrease in the hygroscopic behaviour and an elevation of the resistance to the biological degradation (Militz and Altgen, 2014). Based on the treatment conditions, thermal modification can be categorized as mild, moderate and intensive treatments wherein each one produces varying degrees of property improvement and associated decrease in mechanical strength.

The most sensitive parameter of determining the consequence of thermal modulation is temperature. The majority of thermal modification processes in the industrial sector take place within the range of temperatures between about 160 -260 o C. Below the temperatures, few chemical reactions take place with the major one being the partial degradation of hemicelluloses and slight modification in moisture sorption behaviour. With further rise of treatment temperatures (above 200 0 C) more radical chemical reaction occurs such as large scale hemicellulose degradation and lignin condensation reactions, that greatly enhance dimensional stability and decay resistance, (Tjeerdsma and Militz, 2005; Boonstra, 2008).

Besides temperature, the treatment environment is a decisive factor that can control thermal degradation and avoid excessive oxidation. Thermal modification is normally performed in a setting like inert gas atmosphere (e.g., nitrogen) or in superheated steam, vacuum, or hot oil. Such environments restrict the supply of oxygen and consequently lowers the risk of combustion and gives a chance to a more manipulated chemical reaction within the wood structure (Militz, 2002). The steam based process like ThermoWood process uses water vapour as a protection medium and a heat transfer agent whereas the oil based process depends on hot vegetable oils to offer even heat distribution and extra hydrophobicity (Hill, 2006).

Thermal modification processes are usually categorized according to the treatment medium and the sequence of treatment. The processes that are set commercially are: dry-heat treatment in an inert gas, hydrothermal treatment with steam, and combined treatment processes which are characterized by consecutive heating, cooling and conditioning. The result of every process is thermally modified wood with unique properties, which show differences in heat-transfer processes, chemical-reaction patterns, and the severity of treatment (Militz and Altgen, 2014).

Discussion. Thermal modification has a number of benefits over chemical modification of wood in respect to environmental friendliness and regulatory approval. The chemical modification methods which include acetylation or impregnation of preservative chemicals entail the addition of reactive substances that might be harmful in terms of environmental or health impacts in practice, use, or disposal (Hill, 2006). These techniques may be used to offer better durability and high retention of strength, but they may be expensive in that they have to be handled with strictness and regulation. Conversely, the thermal modification leads to the formation of chemical altered material but devoid of additives, which makes it desirable in an environmentally-friendly and sustainable application.

Another category of wood modification techniques is mechanical modification which includes densification and compression. The techniques enhance mechanical performance by modifying the structure of wood physically stressing it through pressure and deformation, usually along with heat and moisture. Although mechanical modification can go a long way to enhance density and strength, these effects are often reversible except where thermal or chemical stabilisation is used (Navi & Sandberg, 2012). Thermal modification offers instead permanent hygroscopicity and dimensional stability alterations but tends to lead to lower mechanical strength, which underscores trade-offs between the various modification approaches.

In general, the thermal modification takes a very specific place of the technologies of wood modification. It offers a good compromise between enhanced durability, dimensional stability, and sustainability in the environment with reduced mechanical performance. The basic concepts on which the thermal modification is based such as the temperatures, treatment conditions, and performance comparison with other forms of modification is important in order to maximise the process parameters and the application where thermally modified wood is used.

Thermal Modification Processes and technologies.

Various routes of the thermal modification of wood are possible, which vary mostly in the treating atmosphere, heat transfer fluid, and in the order of sequence. These technological differences have a potent impact on the chemical reactions which take place in the cell wall of wood and, therefore the end result of the thermally modified product. The main aim of any thermal modification technology is to increase the dimensional stability and durability and reduce the oxidative degradation and excessive loss of strength (Hill, 2006; Esteves and Pereira, 2009).

Having a heat treatment in an inert atmosphere is one of the oldest and most basic methods of thermal modification. During this, the wood is exposed to high temperature of about 180 0 -260 0 C and no oxygen is present under inert gas like nitrogen. The inert atmosphere avoids combustion and restricts oxidative reactions, enabling the thermal degradation of wood polymers, specifically hemicelluloses, to be controlled (Militz, 2002). The inert heat treatment enhances lignin condensation reaction and decreases the count of available hydroxyl groups, thus enhancing hydrophobicity and biological resistance. Nevertheless, the temperature and exposure time need to be strictly controlled, as the loss of mechanical strength in case of excessive severity of treatment is also considerable (Bourgois & Guyonnet, 1988).

One of the most common industrial technologies that is applied is steam-based thermal modification. The steam used in this approach as a protective atmosphere and as a medium of heat transfer is the superheated steam. Steam inhibits oxidative deterioration and promotes equal distribution of heat all through the wood material. One of the most striking examples of such technology is the ThermoWood process that was invented in Finland and includes multi-stage treatment, consisting of the high-temperature heating process, thermal modification, and controlled cooling and conditioning (International ThermoWood Association, 2021). It has been demonstrated that steam-based systems are effective in the reduction of equilibrium moisture content, dimensional stability, and resistance to fungal decay, which makes them the appropriate system to use in the exterior applications of cladding and decking (Militz & Altgen, 2014).

Oil heat treatment is another significant thermal modification option whereby wood is placed in vegetable oils that are heated and are exposed to temperatures that normally range between 180 C to 220 C. The oil acts as a medium of heat transfer as well as a shield between oxygen and thus minimization of the chances of oxidative degradation (Hill, 2006). Besides the thermal effect, oil heat treatment can make the surface of the wood hydrophobic due to the partial uptake of the oil, which leads to an augmented level of water repulsiveness. Research shows that the use of oil-heat-treated wood has better dimensional stability and decay resistance, but greater mass and changes in surface properties could restrict its use in some applications (Sailer, Rapp, and Leithoff, 2000).

A number of commercial thermal improvement processes have been established on the basis of mixtures of these fundamental principles. ThermoWood process is the most recognized and standardized process in the world especially in Europe. Plato 7 The process was created in Europe and is called the Plato 7 process, which consists of three steps; hydrothermal treatment, drying and curing at high temperatures. This is done to reduce the loss of strength but attaining greater durability and dimensional stability (Tjeerdsma et al., 1998). The other prominent technology is the retification which is a technology initially invented in France and it is based on high-temperature reaction when there is a low oxygen concentration. Retification decreases hygroscopicity and increases decay resistance by a considerable amount, but is linked with quite high mass loss and brittle behavior (Bourgois, Bartholin, and Guyonnet, 1989).

These commercial uses may vary in the technical way in which they are carried out, but have common underlying principles that involve the thermal degradation of hemicelluloses and structural rearrangement of lignin. The process is relative to the desired application, the desired property profile, and the economical factor in which the decision of the process is made. The comprehensive knowledge of the technological principles and constraints of any type of thermal modification is consequently needed to enhance the performance of wood and guarantee proper use of the industrialization.

Thermal Modification Chemical Mechanisms.

The thermomodulation processes of wood are mainly regulated by heat-based reactions, which occur in the three major cell-wall polymers, namely; hemicelluloses, cellulose and lignin. All these reactions have the effect of influencing changes in the hygroscopicity, durability, and stability of the material, eliminating the need to add external chemical modulations to them (Hill, 2006; Esteves and Pereira, 2009).

Hemicelluloses are the most thermo-sensitive wood constituents, which experience a high level of degradation during thermal modification. Increased temperatures cause deacetylation and depolymerization of hemicelluloses that result in the release of acetic acid and a parallel reduction of available hydroxyl groups. This is one of the main causes of degradation that result in decrease of the equilibrium moisture content and improvement of dimensional stability of thermally modified wood (Tjeerdsma and Militz, 2005).

Compared with hemicelluloses, cellulose is comparatively more thermally robust; however, cellulose supramolecular structure may be induced to change through thermal treatment. The exposure to heat can enhance the crystallinity of cellulose by selectively removing amorphous areas and thereby lowering hygroscopicity in addition to having an effect on mechanical properties (Bhuiyan, Hirai, and Sobue, 2000).

Through thermal modification, lignin is condensed and interacts by cross-linking reactions. The purpose of these reactions is to increase the relative content of lignin and increase its hydrophobic nature and therefore increase biological degradation resistance. Making lignin darker and more brittle with increased severity of treatment are also linked with modification of lignin (Bourgois et al., 1989).

The loss of hydroxyl groups throughout the wood polymers is one of the basic results of thermal adjustment. The decrease restrains the ability of wood to interact with water molecules to produce hydrogen bonds, thereby reducing the moisture sorption and enhancing dimensional stability (Hill, 2006).

Besides polymer degradation and rearrangement, thermal modification promotes the formation of new chemical compounds, such as degradation products of low-molecular weight, such as furfural and other aldehydes. These substances also affect the colour of wood, odour and durability properties (Esteves and Pereira, 2009).

Thermal Properties Thermoplastic Wood.

Modification of wood by heat results in drastic alterations in the physical characteristics of wood by both heat-induced chemical reactions and microstructural transformations within the cell wall. these changes are mostly in density, interaction of moisture, dimensional stability, colour, as well as thermal behaviour and together these changes can largely dictate the performance of thermally modified wood in real world applications (Hill, 2006; Esteves and Pereira, 2009).

Mass loss is one of the most obvious physical results of thermal modification and it is mainly due to the degradation of hemicelluloses during the thermal process and evaporation of volatile degradation products. Mass loss is more pronounced with an increase in the treatment temperature and duration and is often accompanied by a slight decrease in density. The extent of the change in density varies with species of wood, level of the treatment and process conditions (Boonstra et al., 2007; Repellin and Guyonnet, 2005).

Compared to the untreated wood, thermally modified wood has a significantly different moisture sorption behaviour. Heat treatment lowers the availability of hydroxyl groups in cell-wall polymers resulting in a lower equilibrium moisture content at a given environmental condition. This loss of hygroscopicity reduces the amount of moisture absorbed and increases its protection against the effects of moisture degradation (Siau, 1995; Hill, 2006).

One of the best benefits of thermal modification is improved dimensional stability. This is because reduced swelling and shrinkage occur due to chemical modification of the polymers of wood as well as reduced moisture sorption capacity. It has also been observed through many studies that there is a tremendous decrease in radial and tangential swelling of thermally modified wood and this makes it the most appropriate wood to use in areas that experience varying humidity (Esteves and Pereira, 2009; Tjeerdsma and Militz, 2005).

One of the apparent effects of thermal change that can be easily observed is colour change. Heat-treated wood normally darkens and appears brown to dark-brown which resembles that of the tropical hardwoods. It is explained by the fact that lignin undergoes chemical changes in colour and gives rise to coloured degradation products (furfurals). Along the aesthetic modification, thermal modification may also affect surface roughness and wettability, hence contributing to performance of coating and finishing (Bekhta and Niemz, 2003).

Through thermal modification, thermal conductivity of wood is also influenced, but the changes are moderate in most cases. The decreased moisture content, and little difference in density may result in the decrease of thermal conductivity, thus, increasing the thermal insulating quality of a thermally modified wood. This feature is especially beneficial to construct applications where thermal efficiency is one of the primary factors (Repellin and Guyonnet, 2005).

On the whole, the physical property modification caused by thermal modification has a great improvement of the performance of wood in situations whereby resistance to moisture, dimensional stability and aesthetic appearance play a crucial role. Nonetheless, these advantages are closely interconnected with the severity of treatment and it is necessary to optimise process parameters.

Thermal modifications of wood and mechanical changes in the mechanical properties of wood.

The thermal alteration has a pronounced effect on the mechanical properties of wood and it is mainly as a result of heat-induced chemical degradation and the resulting structure change in the cell-wall polymers. Even though the treatment induces enhancement in a number of physical and durability-related properties, the process typically causes a loss of mechanical strength especially at elevated treatment temperatures (Hill, 2006; Boonstra et al., 2007).

The thermal modification is one of the most regularly recorded effects, which result in a reduction of bending strength often in the form of modulus of rupture. This has been reduced to a great extent by deterioration of hemicelluloses which are major in stress transfer between cellulose microfibrils. As the severity of the treatment increases, the mass loss and polymer depolymerization create a further brittle continuum of materials (Boonstra et al., 2007; Esteves & Pereira, 2009).

The modulus of elasticity (MOE) that indicates the stiffness of wood is not highly influenced as compared to the strength properties. In other cases, less significant increases or insignificant decreases in stiffness have been noted, especially at moderate treatment temperatures. This has been linked with the enhanced crystallinity of cellulose and cross-linking of lignin, which partly counters the strength losses (Bhuiyan et al., 2000; Tjeerdsma and Militz, 2005).

Bending, tensile strength and compressive strength parallel to the grain often show smaller losses compared to compressive strength perpendicular to the grain. According to various studies, thermally modified wood exhibits a significant percentage of its compressive ability which makes it applicable in uses that are characterized by compressive forces in which extremely high dimensional stability is required (Boonstra et al., 2007).

Some of the mechanical properties that are affected the most negatively include impact strength and toughness. Thermal modification reduces the ability of wood to absorb energy before failure leading to brittle nature; this means that thermally modified wood cannot be used in an application where there is dynamic or impact loading (Hill, 2006).

In general, the changes in mechanical properties are greatly dependent on temperature of treatment, time, type of wood, and quality of original materials. Thermally modified wood is therefore typically recommended in non-structural applications in which better durability and dimensional stability are the most important factors compared with the better mechanical performance.

The first benefit of thermal modification is increased biological strength of wood. The chemical composition of wood is modified by heat treatment in a way that it makes the wood less vulnerable to attack by the decay fungi and insects thus enhancing its service life, especially when it is used in the outdoor and high-moisture environment (Hill, 2006; Esteves and Pereira, 2009).

This higher resistance to fungal decay can be attributed to the degradation of the hemicelluloses in the first place, which is an easily accessible nutrient source of other wood-destroying fungi. The subsequent decrease in these carbohydrates restricts the growth and colonization by fungi. In addition, reduction in equilibrium moisture content results in the environment less favorable to fungal growth which also leads to increased decay resistance (Tjeerdsma and Militz, 2005; Hakkou et al., 2006).

Thermal modification has also been reported to enhance insect and termite resistance, with the degree of protection depending on the type of wood used, the degree of treatment and the conditions of exposure. The decreased nutritional content of thermally modified wood together with the chemical transformation of lignin and extractives is significant in curbing insect attack (Weiland and Guyonnet, 2003).

Laboratory and field experiments prove that thermally modified wood has durability as good as moderately durable species or as naturally resistant species. Therefore, due to its environmental concerns, heat-treated wood is more frequently used as the substitute of chemically treated wood in exterior cladding, decking, and landscape in which environmental concerns are the most important ones (Hakkou et al., 2006; Militz and Altgen, 2014).

However, thermal modification is not the ultimate barrier against any biological agents. Thermally modified wood can be prone to degradation in ground contact or permanently wet environment as the treatment does not add biocidal compounds. Precisely, service conditions and application classes should be attentively kept in mind when choosing thermally modified wood products (Hill, 2006).

To conclude, thermal modification is an eco-friendly approach to improving the biological stability of wood by altering its native characteristics instead of using chemical preservatives. This strategy makes thermally modified wood especially appealing when focusing on the application in which the significance of the environmental safety and the adherence to the regulatory standards are the first priority.

Thermal Modified Wood as an Industrial Material.

Thermally modified wood has gained extensive industrial acceptance due to its improved dimensional stability, decreased hygroscopicity, improved biological stability and good aesthetics as darkened appearance. As a result, the properties make it especially appropriate in the context of its use in those applications where untreated timber would otherwise be prone to moisture-induced damage and to a biological assault (Hill, 2006; Militz and Altgen, 2014).

One of the main areas where thermally modified wood can be used is exterior use. Timber heat-treated is commonly used in the veneering of the facades, decking, window frames, and outdoor furniture. Reduced shrinkage, swelling under varying humidity, increases the stability of shapes and minimizes surface cracking, and the enhanced decay resistance increases the service life without additional chemical preservatives (Esteves & Pereira, 2009; Hakkou et al., 2006).

Thermally modified wood is commonly used in interior purposes either in the flooring, wall panels, saunas or furniture components. The matured moisture activity and color changeouts which are pleasing to our eyes after heating the material is greatly appreciated in these aspects. As an example, thermally treated wood is associated with improved thermal stability, reduced resin leeching, greater moisture and heat resistance (International ThermoWood Association, 2021) when it comes to the building of a sauna.

Wood that is thermally modified is also finding use in landscaping and non-load bearing construction structures including pergolas, fences and shading structures. Despite the tendencies to diminish the mechanical strength in contrast to untreated timber, remnant rigidity and enhanced durability allow the use of such timber safely in the applications with a restricted structural load and when long-term dimensional stability is needed (Boonstra et al., 2007).

Thermal modified wood has no biocidal protection and has lower impact resistance that makes it unsuitable to use in ground contact or the heavy structural use. Therefore, to achieve acceptable long-term performance, it is important to make informed choices of classes of application to use and adhere to appropriate standards (Hill, 2006).

Altogether, the list of possible industrial applications is increasing and demonstrates the rise of the level of trust in thermal modification as an effective and efficient technology of wood improvement in the context of sustainability.

Conclusions and Future Perspectives.

Thermal modification of wood is an established methodology, environmentally safe, of enhancing timber performance with heat-generated chemical and structural changes. The process mainly affects hemicelluloses, cellulose and lignin leading to decrease in hygroscopicity, dimensional stability and increasing resistance to biological degradation. These changes have a great impact on the usability of wood in the moisture-exposed and biologically hostile environments.

Although it is evident that the beneficial effects of thermal modification exist, the method has certain intrinsic constraints, such as a reduction in mechanical strength and an increase in the brittle nature at higher levels of treatment. Based on this, thermally modified wood is most appropriate to non-structural processes in which durability and stability are more important than load-bearing.

The research must be optimized to balance property improvement and strength retention in future studies by way of treatment parameters and by coming up with hybrid modification techniques by integrating thermal treatment with surface coating or mild chemical treatment. Besides, life-cycle assessments and long-term field performance research are the necessities to support the validity of the environmental advantages and service-life projections of thermally-modified wood products.

Given the trend of increased demand on sustainable construction material and minimized use of chemical preservatives, thermal modification is expected to have a crucial role to play in the wood industry. Further innovations and scientific wisdom will further increase its uses and help in the sustainable exploitation of forest resources.

References

1. Bekhta, P., & Niemz, P. (2003). Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. Holzforschung, 57(5), 539–546. https://doi.org/10.1515/HF.2003.080
2. Bhuiyan, M. T. R., Hirai, N., & Sobue, N. (2000). Changes of crystallinity in wood cellulose by heat treatment under dried and moist conditions. Journal of Wood Science, 46(6), 431–436. https://doi.org/10.1007/BF00765800
3. Boonstra, M. J. (2008). A two-stage thermal modification of wood (Doctoral dissertation, Ghent University).
4. Boonstra, M. J., Van Acker, J., Tjeerdsma, B. F., & Kegel, E. (2007). Strength properties of thermally modified softwoods and their relation to polymeric structural wood constituents. Annals of Forest Science, 64(7), 679–690. https://doi.org/10.1051/forest:2007048
5. Bourgois, J., & Guyonnet, R. (1988). Characterization and analysis of torrified wood. Wood Science and Technology, 22(2), 143–155. https://doi.org/10.1007/BF00355850
6. Bourgois, J., Bartholin, M. C., & Guyonnet, R. (1989). Thermal treatment of wood: Analysis of the obtained product. Wood Science and Technology, 23(4), 303–310. https://doi.org/10.1007/BF00353246
7. Esteves, B., & Pereira, H. (2009). Wood modification by heat treatment: A review. BioResources, 4(1), 370–404.
8. Hakkou, M., Pétrissans, M., Zoulalian, A., & Gérardin, P. (2006). Investigation of wood wettability changes during heat treatment on the basis of chemical analysis. Polymer Degradation and Stability, 91(2), 393–397. https://doi.org/10.1016/j.polymdegradstab.2005.04.042
9. Hill, C. A. S. (2006). Wood modification: Chemical, thermal and other processes. John Wiley & Sons.
10. International ThermoWood Association. (2021). ThermoWood® handbook. International ThermoWood Association.
11. Militz, H. (2002). Thermal treatment of wood: European processes and their background (IRG/WP 02-40241). International Research Group on Wood Preservation.
12. Militz, H., & Altgen, M. (2014). Processes and properties of thermally modified wood manufactured in Europe. Drewno, 57(191), 5–26.
13. Navi, P., & Sandberg, D. (2012). Thermo-hydro-mechanical processing of wood. EPFL Press.
14. Palani, P. M. R. (2025). Residential Crisis in Iraq: The Current Trends and Future Prospectus: A Review. Spanish Journal of Innovation and Integrity, 38, 121–128. Retrieved from https://sjii.es/index.php/journal/article/view/185
15. Palani, P. M. R. (2025). The Relationship of International Loans to Credit Wall (Worthiness): A Review. Spanish Journal of Innovation and Integrity, 38, 1–7. Retrieved from https://sjii.es/index.php/journal/article/view/168

16. Repellin, V., & Guyonnet, R. (2005). Evaluation of heat-treated wood swelling by differential scanning calorimetry. Holzforschung, 59(1), 28–34. https://doi.org/10.1515/HF.2005.005
17. Sailer, M., Rapp, A. O., & Leithoff, H. (2000). Improved resistance of Scots pine and spruce by application of an oil-heat treatment. IRG/WP 00-40162. International Research Group on Wood Preservation.
18. Schmidt, O. (2006). Wood and tree fungi: Biology, damage, protection, and use. Springer.
19. Siau, J. F. (1995). Wood: Influence of moisture on physical properties. Virginia Polytechnic Institute.
20. Stamm, A. J. (1956). Thermal degradation of wood and cellulose. Industrial & Engineering Chemistry, 48(3), 413–417. https://doi.org/10.1021/ie51398a022
21. Tjeerdsma, B. F., & Militz, H. (2005). Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. Holzforschung, 59(5), 552–557. https://doi.org/10.1515/HF.2005.089
22. Tjeerdsma, B. F., Boonstra, M., Pizzi, A., Tekely, P., & Militz, H. (1998). Characterisation of thermally modified wood: Molecular reasons for wood performance improvement. Holzforschung, 52(4), 345–352. https://doi.org/10.1515/hfsg.1998.52.4.345
23. Weiland, J. J., & Guyonnet, R. (2003). Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy. Holzforschung, 57(2), 172–176. https://doi.org/10.1515/HF.2003.025