Thermal Modification processes, properties, and environmental impacts

by

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April 2020

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An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Honours Bachelor of Science in Forestry

Faculty of Natural Resources Management

Lakehead University

April 2020

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ABSTRACT

Kumer, E.J. 2020. Thermal treated wood and Modification processes, properties, and environmental impacts .pp 46.

Key Words: thermal treatment, heat treatment, environmental impact, bioeconomy, thermal modification

This paper explores the different ways wood is thermally treated in particular looking at thermal treatment processes, properties produced, environmental impacts and market opportunities. Review is done on different processes that are currently on the market and the properties that are developed through thermal modification such as advances in thermal treatments such as colour stability, dimensional stability, and durability against pests and fungi. Of all the variations of wood modification studied, thermal treatment is the most advanced commercially. The pros and cons for different thermal treatments are looked at and compared. The thermal modification of lumber is recognised as a method to improve the dimensional stability. This review looks at discrepancies of thermal treatments and the environmental consideration of the different procedures. The objective of this thesis is to conduct a review of published literature regarding thermal wood modification processes, properties, environmental impact and market opportunities.

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ACKNOWLEDGEMENTS

I would like to thank my thesis advisor Dr. Mat Leitch for assisting me in the creation of this thesis, along with Scott Miller who helped me throughout this project with any questions I had. I would also like to thank everyone who I have spoken with and consulted with for helping give me insight to this emerging sector and who assisted with this project in any way.

1.0 INTRODUCTION

As a natural renewable resource, wood is an easily accessible, nontoxic and inexpensive biomass material. Although wood is used for many reasons due to its material properties (aesthetic appearance, strength to weight ratio etc.), it also contains some disadvantages. Modifications are applied to the wood to overcome the disadvantages of the wood properties that are mainly related to moisture sensitivity, low dimensional stability, hardness and wear resistance, low resistance to bio-deterioration against fungi and termites (Sandberg et al. 2016). The increased interest has depended on the restricted use of toxic preservatives. Recently environmental concerns have forced industries to examine and demonstrate the environmental impacts of their products. The term environmentally friendly is used far to frequently when describing a product, it needs to be known that all industrial processes have an associated environmental impact. Recently environmental concerns have forced industries to examine and demonstrate the environmental impacts of their products. It's a matter of using products that have the lowest impacts on our environment and should note that all choices should follow principles of sustainability.

Wood modification is looked at to enhance the physical, mechanical and aesthetic properties of wood products. Development of wood processes are looking to limit the impact of the product development, and produce a product that can be disposed of at the end of its life cycle that will not cause environmental impacts greater than the disposal of untreated wood. Currently industries are undergoing changes to the way they are processing the lumber, driven by the concerns for the environment, the motivation to find alternatives to chemical treated wood is ever expanding. Several wood treatment technologies have developed with the idea to minimise the impacts of the treatments and the disposal of the products.

The increased interest in wood modification to industry and society in general is due to a couple of reasons. The change in wood properties that are produced by different treatments can expand the market opportunities in the bioeconomy and the way we use our wood products. There has also been a realization that laws have restricted wood treatment to using environmentally harmful materials for durability in wood products. The study and implementation of other wood treatments can also introduce the use of rare species, which contain outstanding durability or appearance.

The goal of this paper is to review wood modification technologies that have been developed and introduced into some markets with the focus on thermal modification. Thermal treatments and the properties produced from the treatment will be discussed and looked at for the environmental impact in regards to the current wood industrial processes.

1.1 Objective

The objective of this paper is to assess and review the different desired and undesired properties that are developed when thermally modifying wood. Also looking at industrial processes of thermal modification that have been developed and put into the market, and assessing the environmental aspect that is associated with the process and products developed. This paper also looks at the potential development of new environmentally friendly products produced from thermal modification and new market opportunities in the bioeconomy.

2.0 Thermal modification

The basics of thermal modification have been known for a very long time and include several different methods. According to CEN (2007) thermally modified timber (TMT) is wood that has alteration to the macromolecular structure of the wood through the use of heat and moisture in conditions of decreased oxygen availability. On a commercial scale raw lumber is heated between the temperatures of 160° and 240° C to give you thermally modified wood. Temperatures that exceed 240°C degrade the wood to the point where it’s commercially useless (Hills 2021). The result of thermally modified wood alters the wood to a darker color, improves dimensional stability, and increases microbial resistance when compared to the raw lumber. The down side is that there is significant reduction in strength, and fracture resistance. The thermal treatment induces chemical changes to macromolecular structure resulting in alterations to biological and physical properties of the wood, these properties include (Callum 2006):

Table 1. Desirable and undesired properties of TMT

<table>
<tr><th>Desirable properties of TMT</th><th>Undesired properties of TMT</th></tr>
<tr><td>High resistance against decay
High dimensional stability
Lower EMC
Lower thermal conductivity</td><td>Decreased MOR and MOE
Decreased impact strength
Increased brittleness
Decreased hardness</td></tr>
<tr><td colspan="2">Colour change to become darker</td></tr>
<tr><td colspan="2">Distinct smell to TMT</td></tr>
<tr><td colspan="2">Lower density</td></tr>
</table>

The properties of thermally modified wood are highly dependent upon the type of thermal treatment implemented. There are a variety of thermal modification methods that can be applied to wood, and the exact method of treatment can have a significant effect upon the properties of the thermally modified timber (Callum et al. 2006). Some of the important aspects involved in thermal treatment that alter the properties are shown in Table 2.

Table 2. Components that have significant influence over the properties achieved throughout thermal modification.

Important components altering thermal treatment
Time & temperature of treatment Closed vs open system Treatment atmosphere Wet and dry systems Sample dimensions Wood species Use of catalysts

2.1 Chemical Alterations

During any thermal heat treatment the cell wall compounds in the wood are degraded. The components affected are hemicellulose, cellulose, lignin and extractives seen in figure 1. The alteration of the components occurs during different stages of the treatment, and the extent of the alteration depends on the duration and the temperature of the treatments applied. At temperatures from 20-150°C the wood begins to dry, 180-250°C the wood begins undergoing important chemical transformations, and at temperatures above 250°C the carbonization processes with formation of CO_2 and other pyrolysis products develop (Esteves 2009).

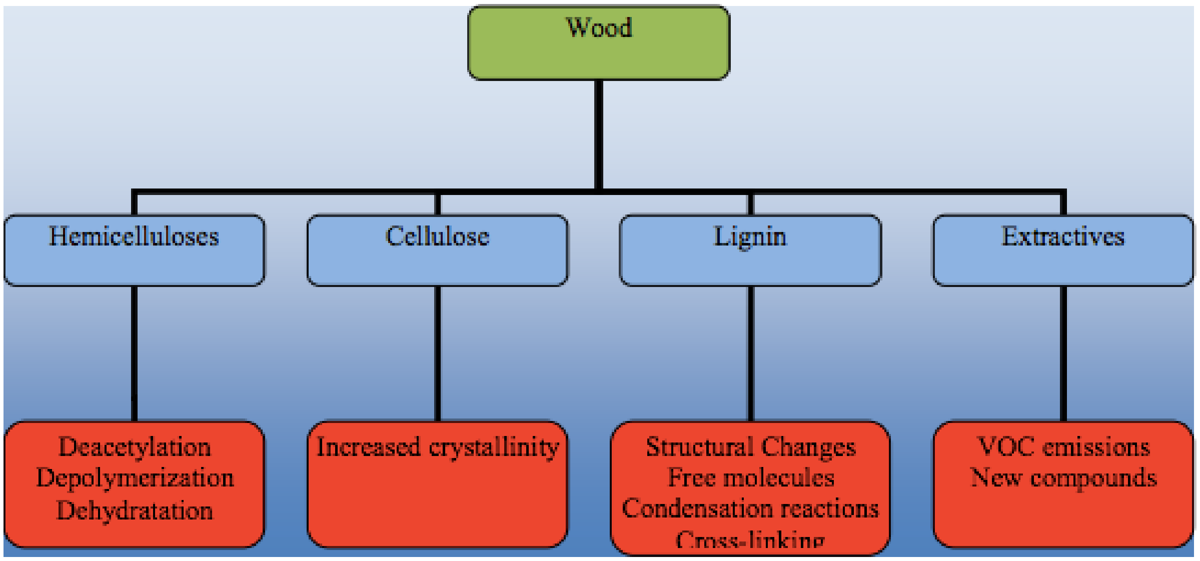

Figure 1. Shows the 4 different components Hemicellulose, cellulose, lignin, extractives that are affected from thermal treatment and the results associated with the alteration of each component (Esteves and Pereira 2009).

Hemicellulose is the first structural compound to be affected by low thermal applications. The degradation starts by deacetylation, and the released acetic acid acts as a depolymerization catalyst that further increases polysaccharide decomposition (Tjeerdsma et al. 1998; Sivonen et al. 2002; Nuopponen et al. 2004). The loss of hemicelluloses causes an increase in the crystallinity of wood samples and also in addition changes degradation and rearrangement of the amorphous cellulose content (Kim et al. 2001). Cellulose degradation occurs at a higher temperature than hemicelluloses, it is thought that minor thermal degradation does occur at relatively low temperatures, but at a much slower rate than the hemicelluloses. The amorphous regions of cellulose are more susceptible to thermal degradation and these regions probably exhibit similar thermal properties to the hexose components of hemicelluloses (Hills 2006). Crystalline cellulose degrades in the temperature range 300–340°C (Kim et al. 2001). It was discovered that the percent of cellulose degraded is reduced with the presence of water; this is due to the ability of the amorphous regions to change structure to produce more thermally stable crystalline regions (Fengel and Wegener 1989). The loss of polysaccharide material in early stages from heating it leads to an increase in lignin content in treated wood. Generally lignin is the most thermally stable component of the cell wall, but some thermal degradation of lignin can occur at relatively low temperatures, with the production of various phenolic breakdown products (Sandermann and Augustin 1964). During the heating process most of the extractives disappear or degrade especially the most volatile, but new compounds are developed and can be extracted from the wood. Bourgois (1989) and Nuopponen (2003) reported extraction of carbohydrates, tannins, resins, fats and waxes. Despite the fact that most of the original extractives are lost from the wood with the heat treatment, the extract content increases greatly with mass loss followed by a decrease (Esteves et al. 2008). Table 3 presents the loss of lignin, extractives and carbohydrates at temperatures from 205-230°C at durations of 4-8 hours for Pine and Birch (Zaman et al. 2000).

Table 3. Pine (*Pinus sylvestris*), and Birch (*Betula pendula*) compared to see the loss of lignin, extractives and carbohydrates at temperatures from 205-230°C at durations of 4-8 hours (Zaman et al. 2000).

Pinus sylvestris			
heat treatment (C/h)	Lignin	Extractives	Carbohydrates
No treatment	24.5	3.2	72.3
205/4	30.1	3.8	66.1
205/6	30.5	2.7	66.8
205/8	32.3	3.2	64.5
230/4	35	3	62
230/6	37.1	4.4	58.5
230/8	38.7	3.8	57.5

Betula pendula			
heat treatment (C/h)	Lignin	Extractives	Carbohydrates
No treatment	21.8	2.6	75.6
205/4	26.3	5.7	68
205/6	28.1	6.7	65.2
205/8	30.6	7.8	61.6
230/4	35.4	8.3	56.3
230/6	35.1	8	56.9
230/8	35.8	8	56.2

2.2 Physical properties

Most properties of TMT are associated to properties of the raw material, affected by the intensity of the thermal treatment process, ie by the temperature and duration of the process (Sandberg et al. 2016). Observing different studies to evaluate the different properties significantly influenced by thermal modification such as mass loss, dimensional stability, colour change, resistance against Fungi and insects, and mechanical properties are presented below.

2.2.1 Mass Loss

Mass loss of wood is considered one of the most important features in heat treatment and is commonly referred to as an indication of quality (Esteves et al. 2009). The reduction in weight is a common effect across all the thermal treatments, due to degradation of carbohydrates and reduction in moisture content held in the wood. The loss in mass changed depending on the species being treated, and the extent of the temperature in the process (Figure 2). As the wood is heated, an initial decrease in weight is from the loss of bound moisture and volatile extractives (Esteves et al. 2008). As temperature is increased during the process, chemical changes to the macromolecular components of the cell wall occur, causing further weight loss (Esteves et al. 2008). The equilibrium moisture % is also a big part that has to do with the final weight of the product. Looking at figure 3 it shows clear resemblance between loss of weight and loss of equilibrium moisture content follow with the increased intensity of thermal treatment.

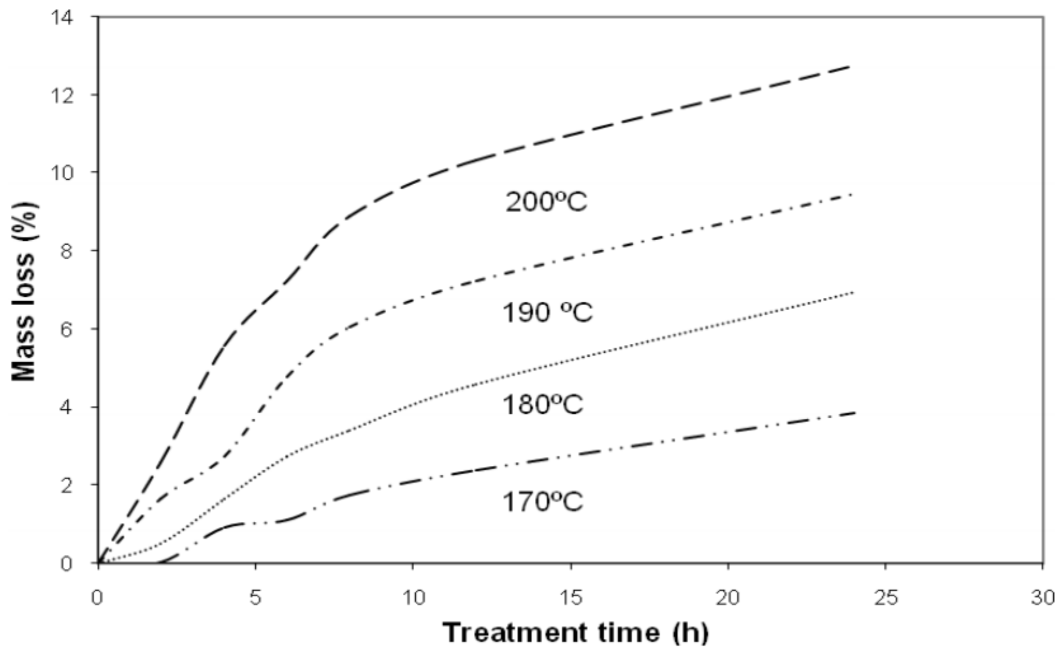

Figure 2. Shows relation of mass loss deration of time and temperature done on pine (Esteves et al. 2008).

The most notable difference in mass loss between species has to do with softwoods and hardwoods, with the mass loss generally being higher in hardwoods (MacLean 1951; Zaman et al. 2000; Militz 2002). Zaman et al. (2000) presented research showing the difference between a hardwood and softwood at temperatures between 205°C -230°C for 4-6-8 hours (Table 4). Total mass loss of the Pine (*Pinus sylvestris)* samples during heating at 205°C and 230°C varied in the range 5.7-7.0 and 11.1-15.2%, respectively, revealing the clear bearing of temperature on overall mass loss. Looking at the birch (*Betula pendula*) data in Table 4, it further supports the link between the increased temperature of treatment and overall mass loss. Furthermore, birch samples degraded slightly more than the pine samples; at 200°C and 225°C the corresponding mass losses in the birch samples were in the range 6.4-10.2 and 13.5-15.2%, respectively.

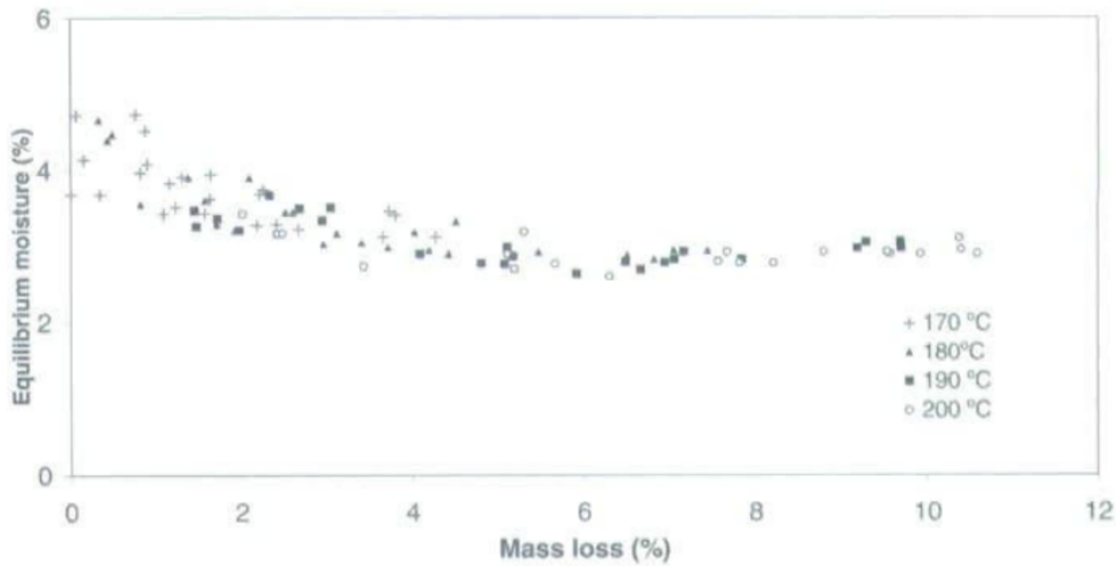

Figure 3. Shows relation between the mass loss in wood in relation to the equilibrium moisture (Esteves et al. 2007).

Table 4. Compares the weight loss between Pine and Birch through different temperatures of 205-230 at 4,6,8-hour intervals (Zaman et al. 2000).

Pinus sylvestris	
Heat treatment (C/h)	Total mass loss %
205/4	5.7
205/6	6.8
205/8	7
230/4	11.1
230/6	13.2
230/8	15.2

Betula pendula	
Heat treatment (C/h)	Total mass loss %
205/4	6.4
205/6	7.1
205/8	10.2
220/4	13.5
220/6	14.7
220/8	15.2

2.2.2 Colour

One of the desired effects when treating lumber with thermal treatment is the alteration from the species natural colour to a darker hue. Different hues can be achieved depending on the temperature of the process and duration (Hoang 2009). A darkening of the wood occurs, with the colour change being related to the temperature and time of treatment (Hills et al. 2006). As the wood is heated chemical changes to the macromolecular components of the cell wall occurs causing colour change, the higher the temperature the further the degradation and the darker the result of the wood (Figure 4). The alteration in the colour of the wood is uniform through out the entire product. Thermal treatment has the ability to increase low value tree species with a light shade to resemble darker shades that are desired from exotic wood species but for a lower cost (Thermo-Drewno 2009).

In the study done by Betkhta and Niemz (2003), they look at colour alteration in relation to the temperature and treatment effects on bending strength. There was a linear relation between the bending strength and the alteration of colour (Table 5). These results suggested that using color changes in wood it is possible to predict the bending strength of wood.

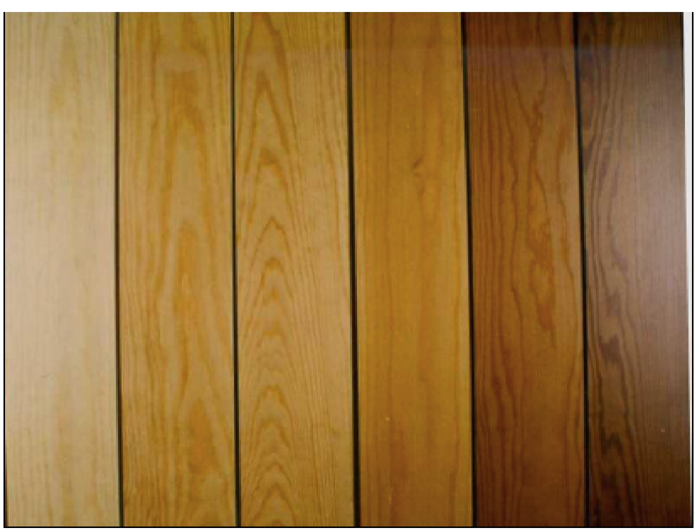

Figure 4. Hues of heat-treated pine from 120 to 210°C (left to right) at 20°C intervals (Thermo wood 2009).

2.2.3 Dimensional stability

Physical properties of wood are altered when it undergoes thermal modification. The process degrades hemicellulose pieces leading to a change in the hygroscopic behaviour of the wood (Hoang et al. 2009). This leads to less moisture being absorbed into thermally modified wood because of the reduction in absorption rate. Chemical processes explain the reduction in dimensional movement in wood after heat treatment. Hemicellulose has high hygroscopic behaviour. Burmester (1975) concludes that heat treatment of wood results in high reduction in the hemicellulose content, and is thus an improvement of the dimensional stability of the wood. The extent of dimensional stability is dependent upon the extent and intensity of the treatment. It was reported that the Antishrink efficiency (ASE) increased with increased time and temperature (Stamm et al. 1946). For example, an ASE of 20 % could be obtained by heating small wood samples either at 150°C for 6 days or at 250°C for 3 minutes (Hills et al. 2006). With improvement in minimizing the water uptake by the wood, this enhances the dimensional stability due to the reduction in swelling and shrinking. Compared to untreated wood, it was found that thermally treated wood was much more stable as shown in figure 5.

This was supported with a study done by Bekhta and Niemz (2003), where wood heated at 200°C becomes more dimensionally stable than wood heated at 20°C due to smaller changes in moisture content. With a treatment duration of 24 h giving more dimensionally stable wood than a treatment duration of 2 h. Swelling both in tangential and radial directions decreased with increases in treatment duration. Bekhta and Niemz (2003) also found that the change in dimensional stability was highly dependent upon the treatment atmosphere employed.

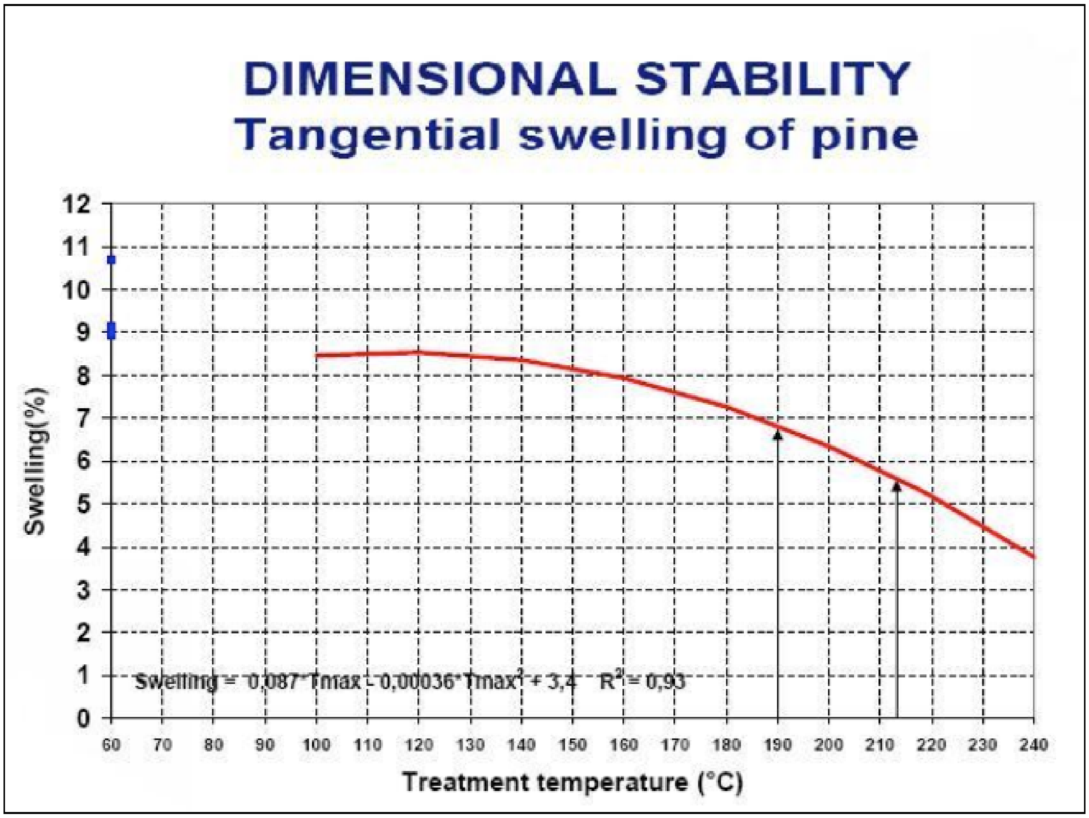

Figure 5. Shows the relation between the treatment temperature and the extent of the swelling of pine post treatment (Hoang 2009).

Three softwood species were studied and these showed very similar behavior. The increase in ASE as a result of heat treatment followed an asymptotic relationship when plotted against weight loss due to heating, reaching a maximum ASE value at about 20% weight loss. However, the results obtained were influenced by the presence of air and lower ASE values were found for a given weight loss compared to anaerobic conditions. Stamm and Hansen (1937) found that heating of dry wood at temperatures ranging from 165°C to 205°C for up to 6 h resulted in a substantial reduction in ASE, but there was no change when the wood was heated in the presence of water. It was considered that the presence of water suppressed those thermal reactions involving loss of water of constitution. Heating in air was found to result in greater reductions in ASE compared with heating in a reducing atmosphere.

2.2.4 Resistance against Fungi and Insects

Thermal modification of wood has displayed great promise in terms of an economically viable way for production of non-toxic wood materials with improved biological durability (Esteves and Pereira 2009; Welzbacher and Rapp 2007; Candelier et al. 2016). It has been discovered from several authors that thermal modification increases the decay resistance. It has been discovered that the extent of the fungi degradation is dependent on the species, temperature, time, and type of rot or insect. During thermal modification degradation of hemicelluloses and lignin are the leading contributions to the improved fungal resistance. Hemicelluloses are generally considered a key in the hygroscopic behaviour of wood for the development of wood rotting fungi, along with the modification of lignin is also part of explaining the ineffectiveness of fungal enzymatic attacks (Candelier et al. 2016).

These heat-treated wood modifications are represented by mass loss. Various authors compared the weight loss caused by fungal attack to the decrease in mass of wood by heat treatment. The variation in different thermal modifications reveal that the treatment used has a significant variation in the effectiveness of fungi and insect resistances. Gao et al. (2018) looked at the effects of soft rot fungi by assessing the mass loss over a year between hardwood and softwood species. In particular looking at *Phialophora malorum, Phialopora mtabilis,* and *Chaetomium golbosum* effect on for Ash (*Fraxinus*), Beach (*Fagus*), Spruce (*Picea*) and Fir (*Abies*) (Figures 6 and 7). It was noted that softwoods have a higher resistance to soft rot than hardwoods. Observations of hardwood TMWs indicate that enhanced decay resistance to soft rot fungi is closely related to delay in formation of typical soft rot cavities in TMWs, particularly at high TM temperatures (Gao et al. 2018).

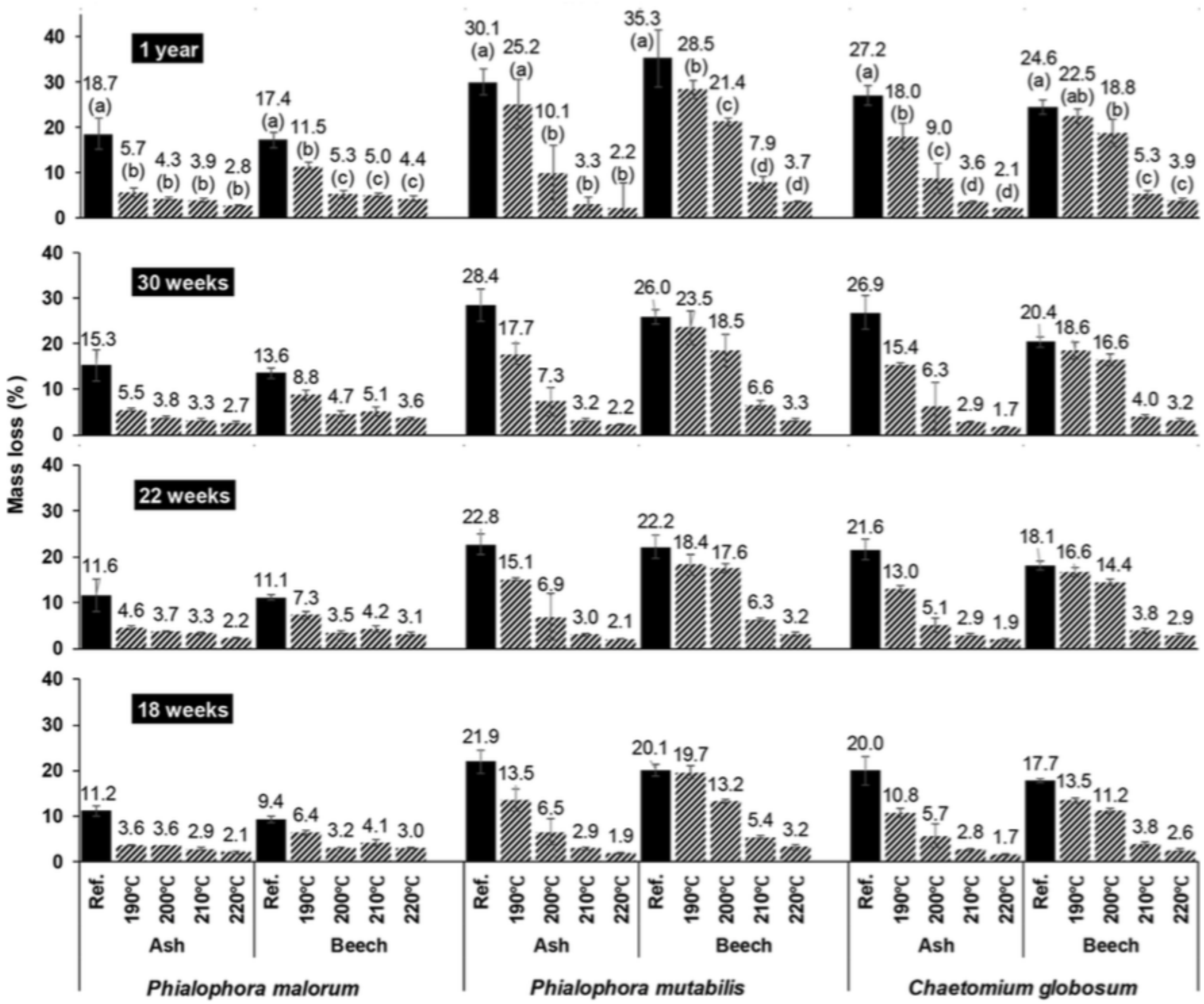

Figure 6. Compares 3 fungi *Phialophora malorum, Phialophora mutabilis, Chaetomium globosum* in relation to the mass loss of different thermally treated hard woods Ash (*Fraxinus*), and Beech (*Fagus*) and untreated wood (Ref.) up to the extent of 1 year (Gao et al. 2018).

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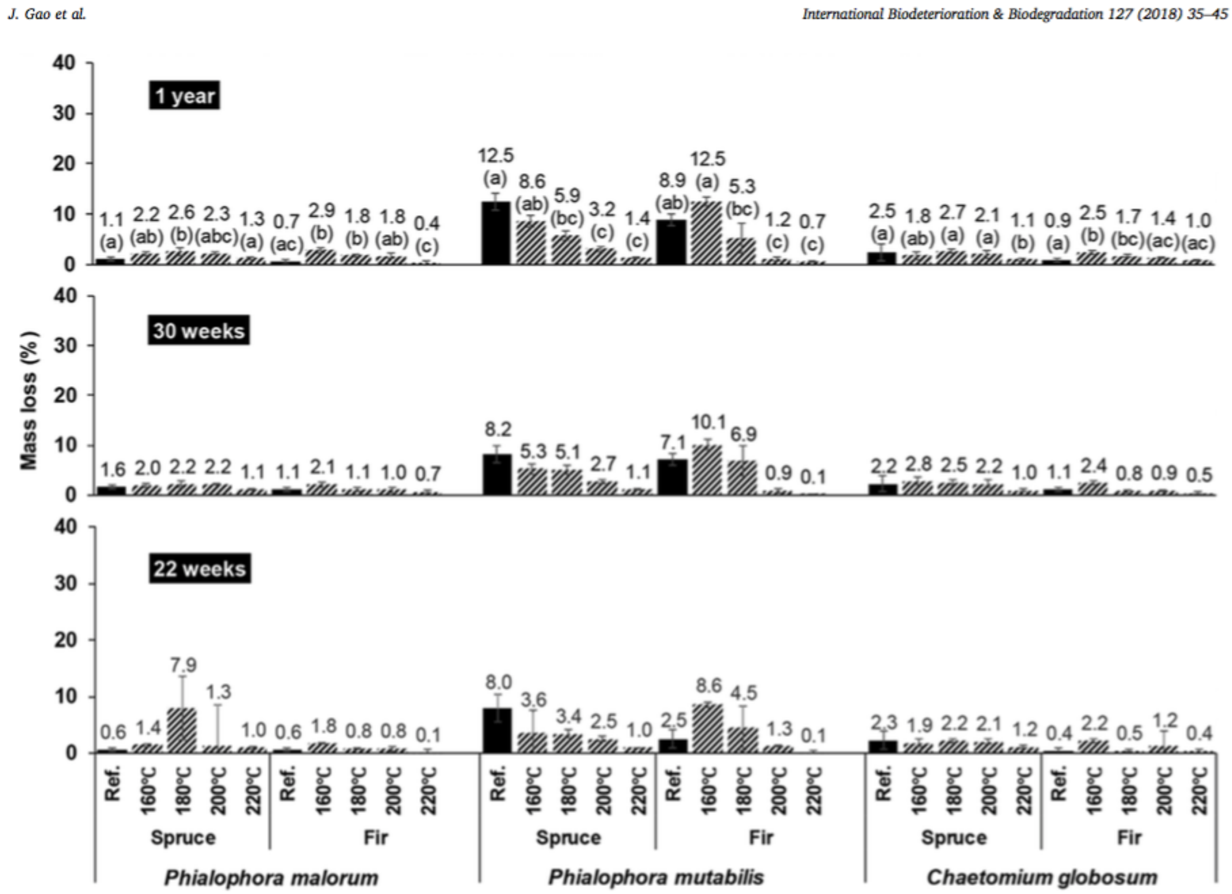

Figure 7. Compares 3 fungi *Phialophora malorum, Phialophora mutabilis, Chaetomium globosum* in relation to the mass loss of different thermally treated hard woods Ash (*Fraxinus*), and Beech (*Fagus*) and untreated wood (Ref.) up to the extent of 1 year (Gao et al. 2018).

In one study conducted by Kartal (2010), it was discovered that white-rot fungus (*T. versicolor*) caused less mass loss than did the brown-rot fungus (*F. palustris)*. This was for specimens that went under treatment at a temperature of 220°C for 2 hours. Another study done by Doi et al. (2004) using the Plato treatment had very little resistance of wood against (*F. palustris)* and (*T. versicolor)*. Another study done by Welzbacher and Rapp (2005) revealed that heat treatment increased the durability of Scots pine sapwood in ground contact for up to 4 years. In a previous study, Kartal (2006) showed that heat treatment at 180°C for 2 and 4 hours was apparently ineffective against decay by *F. palustris.* However, specimens with heat treatment that where exposed to *T. versicolor* had much lower mass loss than untreated specimens. It was also discovered that two stage heat treatments of wood and dry-heat treatments improved the resistance of wood *against C. puteana* and *T. versicolor* (Tjeerdsma et al. 2002).

The results in fungi resistance have a vast array of results depending on the species, treatment and duration; it requires further study of what treatments improve resistance of which fungi. This makes it difficult for industrial production if it can't follow a set standard for the product. With further research different methods are used to try and determine the grade of fungal resistances through the use of mass loss and colour change.

2.2.5 Mechanical properties

Thermal modification at high temperatures will results in a reduction in strength, toughness and abrasion resistance (Chang and Keith 1978). Studies have been done to show the extent of different treatments on the strength of its product, it was discovered that an open and closed system could influence the strength differently (Stamm 1956; MacLean, 1954). This makes it difficult to compare data as different treatments result in different grades. It is clear that with the use of thermal treatment a reduction in strength is to be expected, but it can be influenced through different systems and atmospheric conditions. For example under hygrothermal compared to hydrothermal conditions, and in air compared to anaerobic conditions (MacLean 1954; Stamm 1956).

Bekhta and Niemz (2003) found that bending strength and modulus elasticity were affected at different treatment temperatures. It was discovered that the strength of spruce decreased 44-50% as the treatment temperature was raised from 100-200°C, but with no effect on modulus of elasticity. It was determined that the bending strength was best when heated at

100°C (Figure 8). When the thermal treatment was raised above 100°C both bending strength and modulus elasticity decreased. Another study done by Poncsák el al. (2007) also revealed the used of thermally modified wood used in adhesive bonding has significantly lower strength properties compared to unmodified wood (Figure 9). It was also determined that hardwoods exhibit higher strength losses than softwoods when treated under the same conditions. It was found that elm and beech were more susceptible to thermal degradation compared to aspen and maple, as determined from toughness measurements of the thermally modified samples (Chang and Keith 1978).

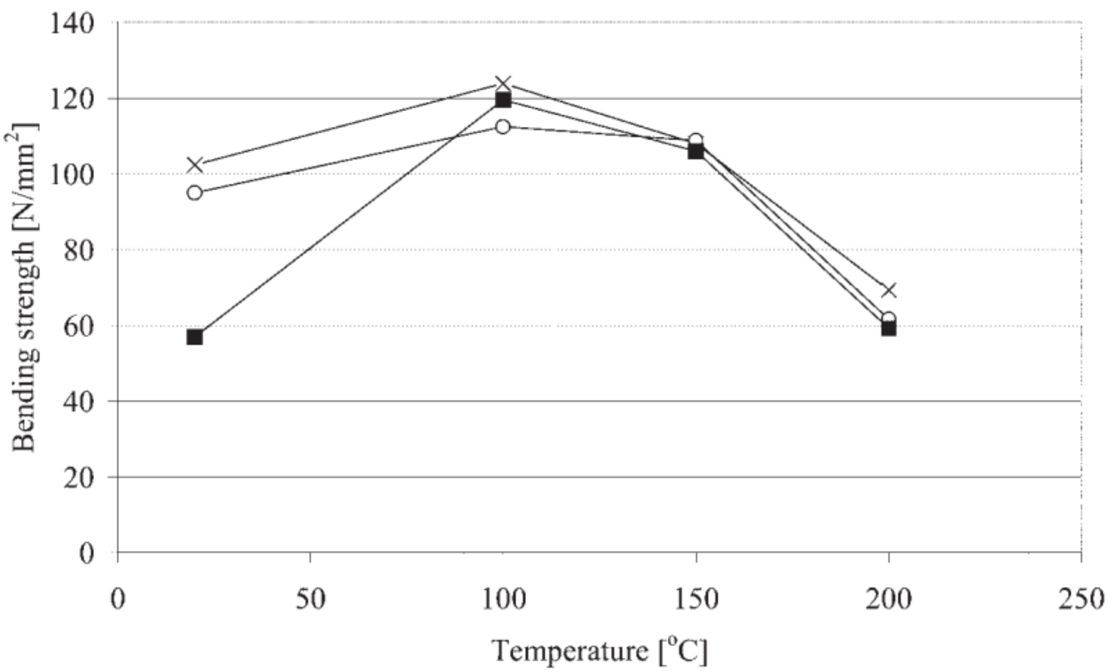

Figure 8. Effect of heat treatment temperature on the bending strength of spruce wood at different relative humidity. ×: RH = 35%; O: RH = 65%; : RH = 95% (Bekhta and Niemz 2003).

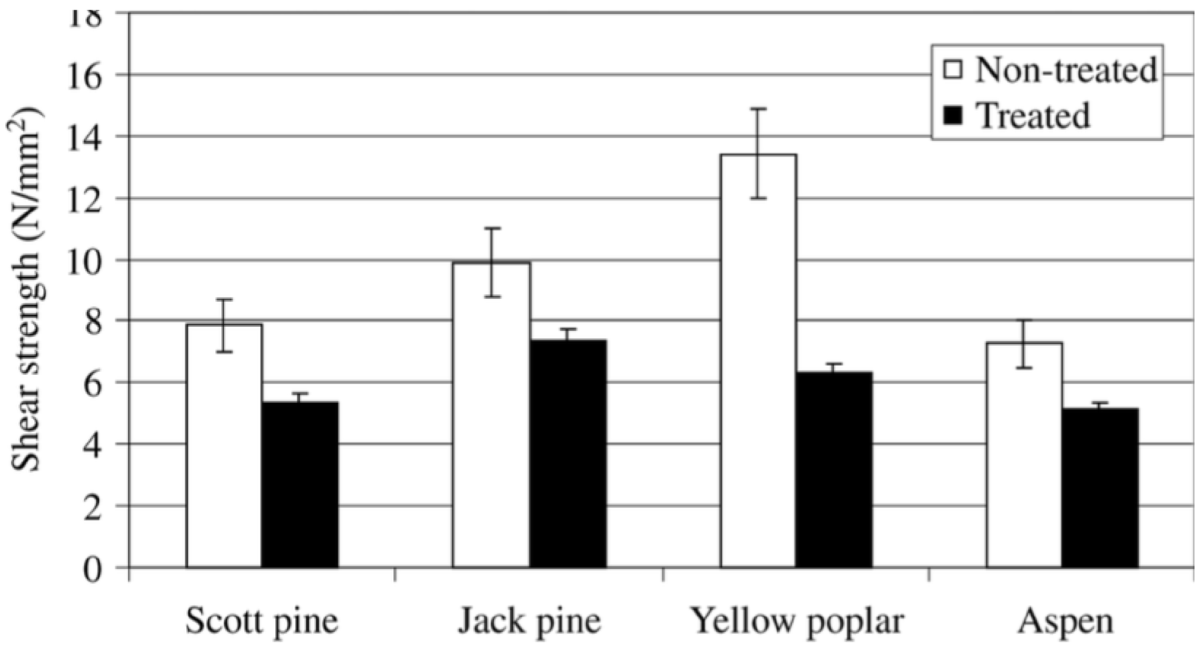

Figure 9. Impact of the thermal treatment on the resistance of the wood–adhesive interface to shear stress, exerted by compression parallel to glued surfaces, of 4 different wood species glued used was polyurethane polymer (Poncsák el al. 2007).

Another property that is displayed from thermal modification is increased hardness. The hardness of wood is a property commonly tested on woods used for paneling, furniture, flooring, decking, products that requires the wood to have resistance to indentation (Leitch 2008). In a study conducted by Leitch M.A (2008), it looks at hardness value of thermally modified Black ash (*Fraxinus nigra)* from Superior thermo wood (STW). For this study the Black ash was treated at 200°C and resulted with a moisture content of 5-8%. It was determined that the STW treatment increases the hardness value of the Black ash when compared with the controls. The increased hardness of the ash was due to cell wall compression, which was observed during the study. It was revealed from this study that thermal modification is effective at increasing the hardness, and aesthetics to create high-valued forest products.

3.0 Commercial thermal modification processes

3.1 Feuchte Wärme Druck (FWD)

Thermally modified treatment of sawn lumber has gained popularity since the start of the 20^{th} century and is now becoming more commercialized. Industrial development of thermal treatments are more popular in Europe then north America, early studies were developed in Germany as far back as the 1940s by using a closed system. Burmester (1973) looked at effects of temperature, pressure, and moisture on wood properties. The process was named the Feuchte Wärme Druck (FWD). The first commercial thermal treatment facility in Europe was based off the study-conducted by Burmester but never produced on a large scale (Sanberg 2016).

3.2 Plato Wood

Intensive development of TMT in Europe gave rise to the Plato process in the Netherlands in the 1980s. It is broken into a 4-stage process (Figure 10) that can take up to 3 weeks from raw sawn lumber to Plato wood (Hills 2006). The first stage is called hydrothermolysis, it takes place in a humid atmosphere and takes from 4-5 hours at temperatures of 160-190°C (Esteves 2009). The second step is the drying process; the wood is dried to the point where it reaches 8%-10% equilibrium moisture content taking anywhere from 5 days to 3 weeks (Hills 2006). The third step is the curing of the wood at the temperature of 150 – 190°C in a dry atmosphere for 12-16 hours; this brings the moisture content to 1%. The fourth and last step is the conditioning where it is placed in a kiln for about 3 days to increase the moisture content to desired levels of about 4-6% when complete

(Hills 2006).

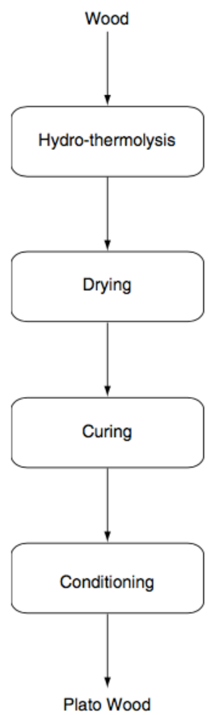

Figure 10. Schematic of the Plato Wood production process (Hills et al. 2006)

3.3 Thermo Wood

In Finland VTT Technical Research Center of Finland worked along side industry to develop the Thermo Wood process in 1993 that got established as an industrial process for improving wood properties (Sanberg et al. 2016). The Thermo wood process is the most advanced heat treatment for wood modification available on a commercial scale. The process occurs in 3 stages and takes up to 40 hours from raw sawn lumber to Thermo wood (figure 11). The first stage is to increase the temperature to dry the wood for about19 hours. During this step a mix of heat and steam raise the temperature of the wood to 100°C for the first 5 hours. The temperature is then ramped to 130°C for the high-temperature drying phase, which reduces the wood moisture content to near 0 %. The second stage is the heat treatment that takes about 10 hours; during this step the temperature in the kiln is increased to 185°C -

230°C and maintained at a target level for 2-3 hours (Hills 2006). The last step is the cooling moisture conditioning, at this point the temperature is gradually lowered using water spray till conditioned to a moisture content of 4%-7%.

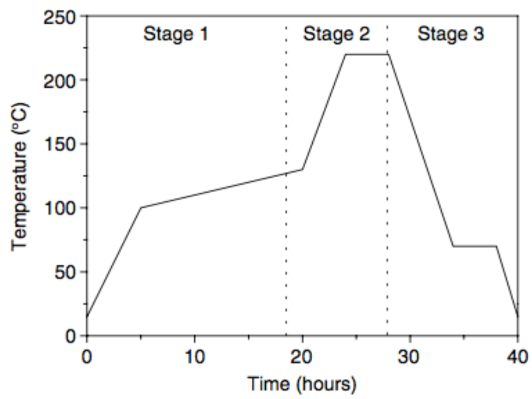

Figure 11. Diagram showing the stages of the Thermo Wood thermal modification process (Hills et al., 2006).

3.4 Le Bois Perdure/ Rectification

Currently two processes are in use in France, the Le Bois Perdure and Rectification. The Le Bois Perdure process starts with green cut wood. The first step starts with the green wood artificially dried in an oven then subsequent heating of wood at temperatures ranging from 200°C - 230°C in a steam atmosphere (Hills et al. 2006; Vernois 2021). Rectification was developed by Ecole des Mines de Saint-Etienne, according to Vernois (2021) the company now holds operating licenses and patents (Also known as RETITECH). The process consists of previously dried wood with a moisture content around 12%, placed in a chamber heated up to 210 - 240°C in a nitrogen atmosphere with less than 2% oxygen (Vernois 2021).

Table 5. Evaluating 4 different commercial thermal modification processes, looking

at the implemented the initial MC (%) used in each (Green= raw sawn lumber) the durations of the processes, type of systems, temperature of application, atmosphere and stages.

Commercial Process	Year	Initial MC (%)	Process Duration (h)	type of system	Temperature C	Atmosphere / transportation median	#Stages
FMD	1970	10-30.	15	Closed	120-180	Steam	1
Plato Wood	1980	Green	2 - 3 wk	Closed	150-190	Steam/ Oxygen 8-10%/ dry	4
Thermo wood	1990	Green-10	30-50	Closed	100-230	Steam	3
Le Bois Perdure	1990	Green	12-36	Closed	230-240	Saturated water vapour	2
Rectification	1997	12	8-24	Closed	200-240	Nitrogen 2% oxygen	1

4.0 Environmental Concerns of Thermal Modification

In the 21st century there has been a great deal of development in the thermal modification field. Despite the fundamental knowledge of the treatment, there is still significant research to be done regarding the process performance and quality of heat-treated wood products, and especially the impact on the environment. The growth and development of thermal modification is encouraged in the Canadian bio-economy. With development it is important to assess the environmental impacts of the treatment and the effect that can be associated with the process. One way to do this is through a life cycle analysis (LCA), it evaluates environmental burdens associated with a product, process, or activity by identifying and quantifying the energy and materials used and the wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements (Thermo Wood 2008). It should reveal the environmental and energy performances of the materials used throughout their whole life cycle from extraction to disposal (Sandberg et al. 2015).

Candelier and Dibdiakova (2020) conducted a LCA review on thermally treated wood and revealed several issues which, lead to question the knowledge behind the environmental impact of thermally based timber processing. In the study two environmental impacts where highlighted one being the energy required to process thermally modified wood and the other concern was the CO_2 emissions produced through the process. The LCA was based off data acquired from several different wood treatment companies but in particular emissions test and energy consumption tests based off Thermo Wood in comparison to imported and chemically treated products.

Assessing the distribution of energy consumption through the drying and heating of ThermoWood Ash (*Fraxinus*) and Spruce (*Picea*) compared to imported Ipe from Brazil and chemically treated Tanalyth E spruce (Figure 12). It was discovered that the Distribution of energy consumption needed for Thermo Wood required more energy to produce than Ipe and Tanalyth E treated species. The high-energy consumption for thermal modification is due to the drying process. It is also notable that the energy required during the process between Thermo Wood Ash and Spruce is significantly different. With the ash being a hardwood it takes almost twice the energy during the drying process compared to the softwood.

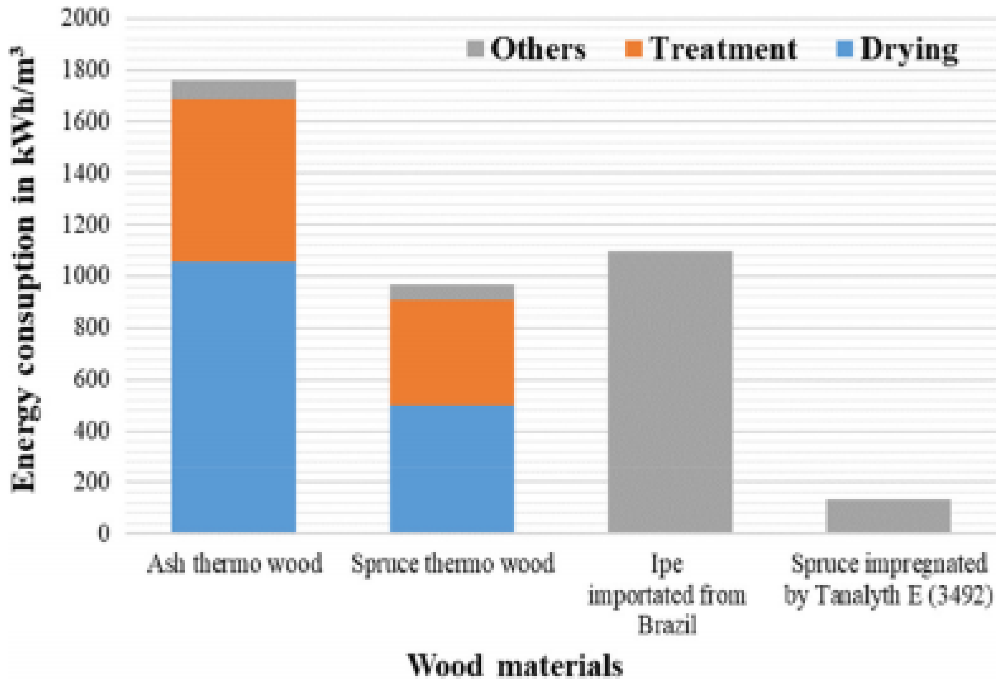

Figure 12. Comparisons between Thermo Wood (ash, and spruce), Ipe imported lumber and impregnated Tanalyth E lumber. Looking at Distribution of energy consumption needed during each process. Energy costs of ash Thermo Wood and spruce Thermo Wood are higher than those of imported Ipe and Tanalyth impregnated spruce. The energy costs are higher for thermally modified ash and spruce woods, due to the high energy use in the drying step (Candelier and Dibdiakova 2020).

The other issue related to the environmental impact of industrial production of thermally modified timber is the release of carbon emissions. The CO_2 is mainly released from the decarboxylation reaction C=O and –COOH groups linked to glucuronic acid units of hemicelluloses (Popescu et al. 2013). The formation of these gasses is dependent on the particular species under treatment and the treatment process used. The release of the gasses also increase with the raise in temperatures when the wood is treated, which in response causes an acceleration of the kinetic reaction of hemicelluloses under the thermal degradation (Xu et al. 2019). Figure 13 shows the data collected from Candelier and Dibdiakoas (2020), it looks at thermally treated Ash, Spruce, Sycamore (*Acer pseudoplantanus*), and Poplar (*Populus*) produced from Thermo Wood and Brimstone, compared to imported Ipe, and chemically modified Spruce. Note Bristone treatment emissions review includes milling, kilning, raw materials electricity, fuel, and transport. This is why there is a significant difference in the difference of CO_2 content emitted by drying compared to CO_2 emitted by other processes. It is clear that the trend in the thermal treatments follows the energy consumption Figure. The carbon emissions released in the thermal treatments where higher than other imported and chemically treated products. The trend also reveals that the CO_2 released is higher in hardwoods than softwoods in both Thermo Wood, and Brimstone thermal treatments. The drying process again was the leading cause in the release of the CO_2 emissions. Based on the results 60 – 80% of the total CO_2 is generated from the initial drying process (Candelier et al. 2020). In some cases to avoid the release of toxic or smelly volatile compounds into the atmosphere is to burn them at very high temperatures during the process (Candelier et al. 2020). Currently today thermo wood developed an ecological solution for recovering volatiles by condensation, purification and filtration successive pro-cesses. Thermo wood is able to retrieve the volatile co-products in the water which is used in the modification process (ThermoWood 2008).

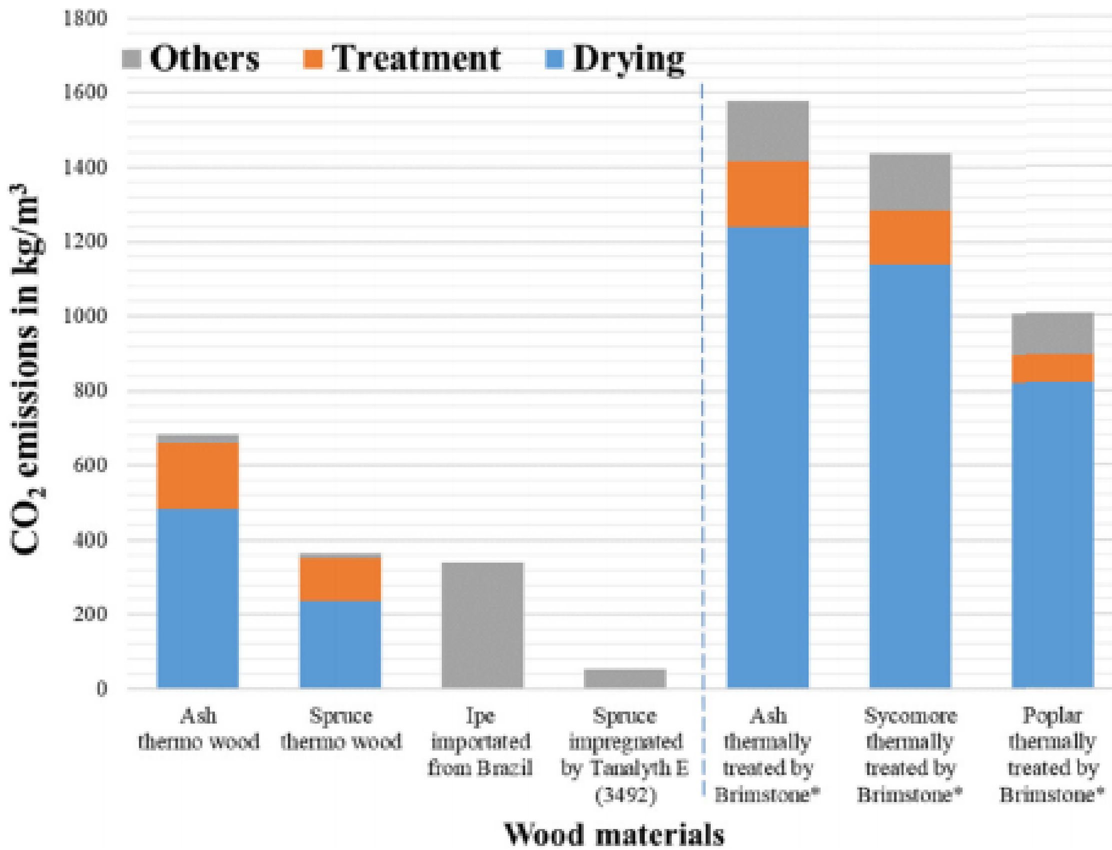

Figure 13. Looking at representations of CO_2 emissions produced from Thermo Wood (ash, spruce), and Brimstone treatments (ash, sycamore, poplar), compared to imported Ipe, and chemically treated spruce. Generally, CO_2 emissions of thermally modified ash, sycamore and poplar woods are higher than those of imported Ipe and Tanalyth impregnated spruce. The elevated CO_2 emissions of thermally modified woods are mainly formed during the drying step (Candelier and Dibdiakova 2020).

For the most part thermal modification is seen as an environmentally friendly solution to wood treatment because of the use of steam and heat and no chemicals. In this case some toxic volatiles compounds are generated during the process. An ecological solution throughout the process is to recover the volatiles through condensation, purification and filtration successive processes (Candelier et al. 2020). This is dependent on the process but for Thermo Wood systems, the volatile co-products are retrieved in the water that is used during the modification process (Thermo Wood 2008). These volatiles are collected to improve the ecofriendly aspect of the treatment but also providing economic benefits that can be gained from the collected volatiles (Figure14). These collected volatiles can be retrieved for a number of uses in other aspects of the timber industry such as wood preservation with furfural (Dautzenberg et al. 2011), antifungal properties of Eugenol (Pfriem et al. 2009), or antitermitic activity gained from terpenes (Bédounguindzi et al. 2020). This data suggests that there can be economic potential from using the co-products produced from thermal wood modification while reducing the environmental footprint of the thermal process. In addition with the release of volatiles during the thermal process it helps to reduce the release of these chemicals during the life cycle of the product compared to those of natural or other chemically modified woods, therefore reducing the impact further. Recovering these volatiles in the stages of thermal treatment can have high added-value components for industry and allow further transformation into wood preservatives (Bédounguindzi et al. 2020; Boer et al. 2020; Brocco et al. 2017) while improving the circular economy and environmental impacts associated with wood heat treatment (Candelier et al. 2020).

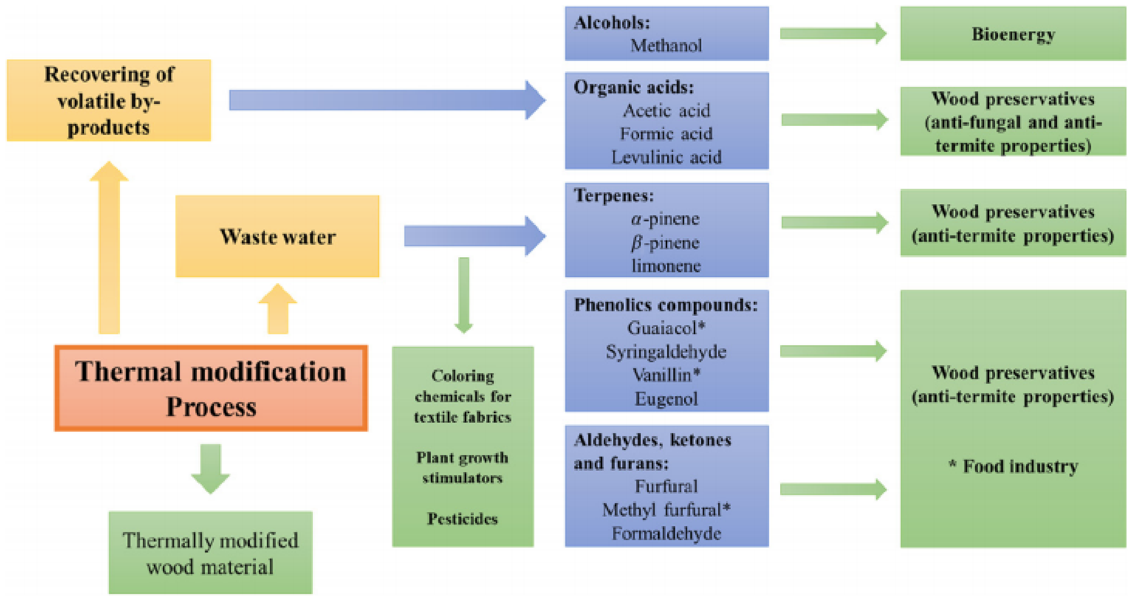

Figure 14. This diagram demonstrated the volatiles that are extracted from the wood during thermal modification process. The diagram also shows what the volatiles are used for and what other products use the volatiles, expanding market opportunities (Candelier and Dibdiakova 2020).

5.0 Bio-economy

The global trade of forest products is changing rapidly under the influence of international competition, and a shift in consumer demand for green products (Duchesne et al. 2003). Today Canada has a clear opportunity to leverage its global forest sector leadership into bio products that will lower our environmental impacts and drive economic growth (Maloney et al. 2018). At this point the world's political and economic decisions will need to be made around the fact of energy scarcity and climate change. In this case a balance needs to be achieved between economic, ecological and social well being that can be summed up into sustainability. Forestry has been put in the spot light to lead the change for sustainability, it is viewed as one of the worlds most utilized sustainable resources, but the one area where forestry fails to appear sustainable is during the production of energy intensive materials. New technologies are being developed in thermal modification in an effort to reduce the wood technological applications without changing eco-friendly characteristics (Sandberg 2016). Even though thermally modified wood only represents a small portion of the timber industry, the product tends to gain more interest each year. Due to recent developments of more environmentally friendly wood treatments, chemical modifications are becoming more limited due to the raising environmental concern and opening new interest in market opportunities for thermal modification. Since the new developments of the thermal modified process was developed in Europe, Canada has begun to establish several production units and research facilities as a result. In Quebec several industrial plants using the Perdure process where developed. The Thermo Wood process was also established, in 2012 with a total of 7 manufacturers of TMT established in Canada (Sandberg 2016).

Thermal modification is the leading wood treatment to become a low environmental impact alternative for wood modification, and it considerably improves wood durability (Marra et al. 2015). The growing environmental awareness has led to a growing interest in these alternative wood modification processes (Gérardin et al. 2016). The development of commercial interest is due to changes in the restriction of conventional chemical products used for wood preservation (Jones et al. 2019). New demand for low environmental impacted treatments (Gérardin 2016), higher use of low value locally sourced timber species (Candelier et al. 2016), and an ever increasing demand for new aesthetics and customer requirements (Gamache et al. 2017) is driving the push.

According to Sandberg and Kutnar (2016) thermal heat-treated wood materials can contribute to mitigating climate change and promoting sustainable development by reducing energy intake, solid and volatile emissions reducing pollution, and ecosystem damage, while increasing wood performance. This can help lead to a low-carbon economy and sustainable development, it is essential to embed awareness of environmental impacts and by-products to wood modification process parameters and product properties and qualities (Candelier et al. 2020). In order to gain an advantage in the market, Canada needs to pursue new alternatives for forest products, while achieving opportunity in the abundance of forest resources and conduct research and development of industry based bioproducts.

6.0 Discussion

The development of thermally modified timber has shown to present improved physical properties. It allows wood to become dimensionally stable, darker in hue, and more resistant to fungi and insects in some cases. Suitable uses indoor and outdoors have been found to benefit from thermal modification. Exterior uses have been found to be used on window and door frames where it is exposed to moisture, Christmas et al. (2007) suggested that due to the brittleness associated with thermal treatment it minimizes the use for doors. The high moisture resistance and fungi resistance make it a good material to use in climates with high humidity or with high exposure to wet environments. Some internal applications consist of: flooring, sauna fittings, and wall/ceiling panels (Hogan et al. 2009). Modified wood can also be used for some external applications such as: cladding, siding, fascia boards, garden structures, and decking (Stora Enso, 2004). Although thermal treated wood is good in moist climates, it should not be buried under the ground. “ Moisture up-take of the cell walls is reduced due to the thermal treatment process, but cell cavities can take up fluid water, similar to untreated wood” (Scheiding et al. 2007).

Thermal modification was also found to have some poor results, strength properties where found to decrease. The alterations of the structure were due to the cellulose and lignin within the wood due to heat, the extent of the reduction in strength was found to increase with increases in temperature. There has yet to be a balance discovered between durability and strength, the higher the treatment the more durable the product, but lower the modulus of rupture. The decrease in strength excludes the use of this product in structural uses and is not possible for industrial use until further studies are carried out and materials are approved.

The thermal modification process offers an environmentally friendly alternative to alter the aesthetics of natural wood. The process can take low valued timbers that isn't utilised in local markets and add increased value with thermal modification. The alteration of colour to low value species resembles the aesthetic value that is desired in exotic species of wood, but for a lower price.

The process of thermal modification is an environmentally friendly alternative to modify wood. Although it is an environmental alternative the process still seems to be working out kinks in the industrial development of the product regarding the environmental impact around the production process. Environmental concerns were discovered to be exhibited with the drying process, with respect to releasing any extractives from the wood into the atmosphere. It was also discovered that high amounts of CO_2 emissions are released into the atmosphere. These are the major concerns with the process, however it also holds major potential for becoming an ecofriendly alternative to chemical treatments with further study.

Since the process only uses heat and water without the use of chemicals, it is believed the risk of harmful chemicals leaching into the environment is minimal if at all.

Thermal modification is growing in interest with development into the bioeconomy as an alternative to chemical treatments. The main developments have been realised in Europe, with industrial production at a number of different processing facilities. New developments of Thermo Wood, Plato wood, Le Bois Perdure, and Rectification has led to a growing popularity in Canada and the USA. There have been several developments of thermal wood modification processing plants developed in North America. With further development of thermal modification it expands market opportunities in the bioeconomy as an environmentally friendly alternative.

7.0 Conclusion

This literature review concludes that several aspects related to heat-treated wood have significant limits that contribute to performance. Further study can reveal potential in future markets as an environmentally friendly alternative for industrial wood products. It is restricted from its poor strength due to alteration to cellulose and lignin during the treatment process, it restricts the use of the product to non-structural uses. Due to the low awareness of the consumer, the popularity of the product is lower than traditional preservative products. The production of thermal modified wood is limited to the exposure and knowledge of the consumers. Although thermal modification has some limitations there is also major potential for the product to develop as a widely used product. Due to the process improving properties such as dimensional stability, colour alteration, and decay resistance without the use of chemicals it is beginning to gain more interest from the common consumer in recent years. Thermal modification has the potential to shift ever changing markets to move away from traditional practices of wood preservation involving chemicals towards thermal modification of wood using only heat and steam.

With current studies and developments of thermal modification the market potential for indoor and outdoor uses regarding décor, due to the aesthetic alteration during treatment, is significant. Until further research is done to fully determine the extent of structural properties, decisions can't be determined to see what changes can be done to adapt it to certain markets. If thermal modification can be developed to offer structural materials and be fungi resistant with good dimensional stability, markets to use thermally modified wood compared to traditional chemical treatments will expand.

Furthermore, through the literature assessed and the LCA reviewed, the thermal modification processes look to provide strong potential to produce environmentally friendly wood products. The process of thermal treatment uses a combination of high heat and steam, without the use of chemicals or other environmentally harmful chemical. Thermal modification is based on the potential for developing green building products (Sandberg et al. 2016). In an ever-changing market and a growth of interest in environmentally friendly products, thermal modification looks to take the stage, but with all development of new technologies there is always room for improvement.

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