A Review of Wood Modification Globally – Updated Findings from COST FP1407

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ABSTRACT

Wood modification (chemical, thermal, impregnation) represents an assortment of innovative processes continually being adopted in the wood protection sector. COST Action FP1407 “Understanding wood modification through an integrated scientific and environmental impact approach — ModWoodLife” was initiated in 2015, with its 4-year programme aiming to investigate modification processing and products design with emphasis on their environmental impacts. Among the final tasks within COST FP1407 was to re-evaluate the current status of wood modification across the member countries. However, it became clear that activities in other European countries needed to be addressed, and as a result, a more extensive evaluation of wood modification processes across Europe was undertaken, as well as determining the activities globally. This paper outlines some of the recent updates in wood modification, along with summarising data collected by the authors from international colleagues and online sources, so providing an evaluation of the overall global position. These figures suggest that wood modification is undergoing a significant increase in production due to demand, with levels of recent growth seemingly suggesting this will continue for the coming years. Based on data gathered, the global commercial production of modified wood is dominated by thermal modification processes, which produce 1,110,000 m³/year. Among the other commercialised processes, acetylation accounts for 120,000 m³/year and furfurylation 45,000 m³/year. A further global production of around 330,000 m³/year is estimated for other processes, predominantly based on resin-based systems (e.g., Impreg- and Compreg-based processes).

Keywords: wood modification, commercialisation, production
1. Introduction

Wood modification (chemical, thermal, impregnation) represents an assortment of innovative processes adopted to improve the physical, mechanical, or aesthetic properties of sawn timber, veneer or wood particles used in the production of wood composites. This process produces a material that can be disposed at the end of a product’s life cycle without presenting any environmental hazards greater than those associated with the disposal of unmodified wood.

As a natural renewable resource, wood is in general a non-toxic, easily accessible and inexpensive biomass-derived material. Since ancient times, wood has been used by mankind based on its inherent properties, meaning that a specific part of a tree of particular specie that could be found in the neighbourhood was utilised to achieve the best performance when it was used in construction, for different types of tools, or for purposes not included in the practical tasks of life. Aside from drying, modification of timber has been rare from a historical perspective. Nevertheless, as wood is a natural product that originates from different individual trees, limits are imposed on its use, and the material needs to be transformed to acquire the desired functionality. This has become increasingly evident in the modern and highly industrial era. Modification is thus applied to overcome weak points of the wood material that are mainly related to moisture sensitiveness, low dimensional stability, hardness and wear resistance, low resistance to bio-deterioration against fungi, termites, marine borers, and low resistance to UV irradiation.

Hill (2006) has provided a well-accepted definition of wood modification:

“Wood modification involves the action of a chemical, biological or physical agent upon the material, resulting in a desired property enhancement during the service life of the modified wood. The modified wood should itself be nontoxic under service conditions, and furthermore, there should be no release of any toxic substances during service, or at end of life, following disposal or recycling of the modified wood. If the modification is intended for improved resistance to biological attack, then the mode of action should be non-biocidal”.

The means by which the majority of wood modification systems occur can be shown schematically (Figure 1).
The wood modification industry is currently undergoing major developments, driven in part by environmental concerns regarding the use of wood treated with certain classes of preservatives. Several fairly new technologies, such as thermal modification, acetylation, furfurylation, and different impregnation processes, have been successfully introduced on the market and demonstrate the potential of these modern technologies. Figure 2 gives an overview of what can be construed as wood modification.

This paper does not focus on the following areas, which have been reviewed elsewhere:

- treatments aiming to improve wood properties such as fire/flame stability (cf. Lowden and Hull, 2013; Visakh and Arao, 2015),
- preservation of ancient small artefacts (cf. Unger et al., 2001),
- wood particles or disintegrated wood mixed with other polymeric material, such as wood plastic composites (cf. Jawid et al., 2017), or
- modification and derivatisation of extensively mechanically and chemically degraded wood constituents (cf. Huang et al., 2019).

The main reasons for the increased interest during the last decades in wood modification through ongoing research, the industry, and society in general can be summarised as:

1. a change in wood properties as a result of changes in silvicultural practices and the way of using wood,
2. awareness of the use of rare species with outstanding properties, such as durability and appearance,
3. awareness and restrictions by law of using environmental non-friendly chemicals for increased durability and reduced maintenance of wood products,
4. an increased interest from the industry to add value to sawn timber and by-products, from the sawmill and refining processes further up in the value chain,
5. EU and international policies supporting the development of a sustainable society, and
6. the international dimension on climate change and related activities mainly organised within the frame of the United Nations (UN), such as the Paris Agreement under the United Nations Framework Convention on Climate Change.

2. COST Action FP1407

COST Action FP1407 (Understanding wood modification through an integrated scientific and environmental impact approach — “ModWoodLife”) aimed to investigate modification processing and products design with emphasis on their environmental impacts. This will require analysis of the whole value chain, from forest through processing, installation, in-service, end of life, second/third life (cascading) and ultimately incineration with energy recovery. The aim of the 4-year Action can be summarised as in Figure 3.

![Figure 3: Overview of COST FP1407.](image)

The Action also allowed the collection of essential data on the status of wood modification from all participating countries, forming the basis of a publication into how the sector had expended in recent years.

3. Wood Modification Methods

The modification of wood has been used as a method to improve the properties of service life of wood for numerous centuries, whether it being the charring or burning of surfaces, or through the application of waxes or oils. An early example of what would today be construed as wood modification was undertaken by Alfred Nobel’s father, Immanuel. His work, patented in conjunction with colonel Nikolai Aleksandrovich Ogarev in 1844, considered the impregnation of wood to be used in carriage wheels with a mixture of ferric sulphate and an acid, which was dried slowly in special boxes. After drying, linseed oil and varnish were applied to further
reduce moisture absorption. The process was also an early example of mechanisation, the process being run by a steam engine, with 36 wheels a day being produced for the Russian army (Tolf, 1976; Meluna, 2009; Carlberg, 2019).

The development of wood modification has focussed on the potential of altering the performance and reduce the risks of wood in service, particularly with regard to dimensional instability and decay, both of which are strongly influenced by the presence of moisture. Wood in service in interior conditions is usually restricted to moisture contents below 10%, but design or exposure to high moisture conditions can significantly affect its performance. The same is true of wood in Use Classes 2 and 3 as defined within the European standard EN 335 (European Committee for Standardization, 2013), where the moisture content can often exceed 20% due to atmospheric conditions. A more detailed description of the Use Classes is shown in Table 1, along with definitions of risks and typical product ranges as defined within a product guidance manual produced by the Wood Protection Association in the United Kingdom (WPA, 2012). The risk of decay is then increased, particularly if the exposure is over a prolonged period of time.

**Table 1: Overview of Use Classes, as defined according to EN 335 (European Committee for Standardization, 2013) and typical product ranges and their associated risks according to the UK Wood Protection Association (WPA, 2012).**

| Use Class | Biological risk | Typical service exposure | Examples of product ranges |
|-----------|-----------------|--------------------------|---------------------------|
| **UC 1**  | Insect          | Internal, with no risk of wetting | All timbers in normal pitched roofs except tiling battens and valley gutter members. |
| **UC 2**  | Fungi/Insect    | Internal, with risk of occasional wetting | Floorboards, architraves, internal joinery, skirtings. All timbers in upper floors not built into solid external walls |
| **UC 3.1**| Fungi/Insect    | External, above damp-proof course, coated | Tiling battens, frame timbers in timber frame houses, timber in pitched roofs with high condensation risk, timbers in flat roofs, ground floor joists, sole plates (above the damp proof course), timber joists in upper floors built into external walls. |
| **UC 3.2**| Fungi/Insect    | External, above damp-proof course, uncoated | External joinery including roof soffits and fascias, barge boards, etc., cladding, valley gutter timbers, external structural load-bearing timbers |
| **UC 4**  | Fungi/Insect (incl. termites) | Timbers in permanent contact with the ground or below damp-proof course. Cooling tower packing. Timbers exposed to the particularly hazardous environment of cooling towers. | Cladding, fence rails, gates, fence boards, agricultural timbers not in soil / manure contact and garden decking timbers that are not in contact with the ground. |
| **UC 5**  | Marine borer/ Fungi | All components in permanent contact with sea water. | Fence posts, gravel boards, agricultural timbers in soil / manure contact, poles, sleepers, playground equipment, motorway and highway fencing / sound barriers and garden decking timbers that are in contact with the ground. Lock gates and canal linings. Cooling tower infrastructure (fresh water). |
A comprehensive review by Thybring (2013) has assessed the decay risk according to levels of moisture exclusion efficiency (MEE), anti-swelling efficiency (ASE), and ASE* (an alternative measure of ASE, where the volume increase resulting from various wood modification methods has been deducted from the dry volume of the unreacted wood). Through the analysis of modification methods undertaken (Table 2), it was possible to estimate threshold levels for MEE, ASE, and ASE* as well as the respective weight gain required for each treatment (a weight loss when considering thermal modification).

**Table 2: Estimated threshold conditions for decay in various wood modifications (Thybring, 2013).**

| Modification       | Threshold (WPG) | MEE  | ASE  | ASE* |
|--------------------|----------------|------|------|------|
| Acetylation        | 20 %           | 42 % | 63 % | 60 % |
| Furfurylation      | 35 %           | 40 % | 74 % | ?    |
| DMDHEU             | 25 %           | 43 % | 45 % | 43 % |
| Glutaraldehyde     | 10 %           | 24 % | 50 % | 48 % |
| Glyoxal            | >50 %          | ?    | ?    | ?    |
| Thermal modification| -15 %          | 42 % | 46 % | ?    |

Where WPG – weight percent gain, MEE – moisture exclusion efficiency and ASE – anti-swelling efficiency.

Moisture has been recognised as a key parameter in the infestation and decay of wood by wood destroying fungi. In addition to the supply of oxygen, a favourable temperature, and accessible nutrients, it is an essential factor in the fungal decay of wooden commodities and structures. For many decades, it was therefore essential to define the critical moisture content thresholds allowing the transport and activity of fungal enzymes in the wood cell walls leading to the degradation and severe rot of wooden elements. Nowadays, the wood moisture content is the most important input variable in many service life and performance prediction models, both in engineering and natural sciences (Brischke and Thelandersson, 2014).

The main forms of wood modification (in terms of commercial development) are acetylation, furfurylation, thermal modification, and resin impregnation/polymerisation. There are a range of other modification methods that have been reported (e.g., Rowell, 1983; Hill, 2006) as suggested in Figure 2 and regularly reported in conferences such as the European Conference on Wood Modification (ECWM) and The International Research Group on Wood Protection (IRG).

### 3.1. Acetylation

The acetylation of wood is a chemical modification process in which the electrophilic reagent (most commonly acetic anhydride) is forced by the application of an external pressure to migrate through the wood pits in conifers and through vessels in broad-leaved species, to react with accessible nucleophilic hydroxyl groups in the wood and to diffuse and react deeper into the cell wall (Rowell, 1983). Thus, bulking of the cell wall and loss of hydrophilic hydroxyl groups reduces the moisture uptake, and increases the resistance to swelling and the decay of wood (Hill and Jones, 1996; Hill, 2006). So far, radiata pine has mostly been used commercially due to its low density and open pore structure, but fibres in acetylated fibreboards can be more easily reacted than the solid wood products, and this can favour the use of other species. The simplified reaction of wood components with acetic anhydride is shown in Figure 4.
Many different types of wood have been acetylated using a variety of procedures including European beech (Fagus sylvatica) (Militz, 1991ab), Norway spruce (Picea abies) (Larsson and Simonson, 1994) poplar (Populus spp.), radiata pine (Pinus radiata) (Bongers and Beckers, 2003), black locust (Robinia pseudoacacia) (Németh et al., 2010), Southern yellow pine, ponderosa pine (Pinus ponderosa) (Goldstein et al., 1961), red oak (Quercus rubra) and sugar maple (Acer saccharum) (Dreher et al., 1964), walnut (Juglans spp.), elm (Ulmus spp.), cativo (Prioria copaifera), Eucalyptus spp. (Rowell, 1984; Ozmen, 2007), rubberwood (Hevea brasiliensis) (Rafidah et al. 2006), poplar (Populus spp.), willow (Salix spp.) (Ozmen, 2007), and oriented strand boards (OSB) (Rowell and Plackett, 1988) as well as other lignocellulosic resources such as bamboo (Phyllostachys bambusoides Sieb. et Zucc) (Rowell and Norimoto, 1987), bagasse (Saccharum officinarum L.) fibre (Rowell and Keany, 1991), jute (Corchorus olitorius) (Callow, 1951; Andersson and Tillman, 1989), kenaf (Hibiscus cannabinus) (Rowell and Harrison, 1993), wheat straw (Triticum aestivum) (Gomez-Bueso et al., 1999), pennywort (Centella asiatica), and water hyacinth (Eichhornia crassipes) (Rowell and Rowell, 1989). A more detailed overview of species and acetylation conditions is given in Table 3.

Table 3: Summary of selected examples of acetylation.

| Species                                      | Acetylation method                                      | Reference                  |
|----------------------------------------------|----------------------------------------------------------|----------------------------|
| Small and medium scale                       |                                                          |                            |
| African locust bean (Parkia biglobosa)       | Acetic anhydride or acetic acid /CaCl$_2$, heating at 120 °C for <3 hours. | Azeh et al., 2013          |
| Caucasian alder (Alnus subcordata C.A. Mey), Oriental beech (Fagus orientalis Lipsky) | Acetic anhydride, soak 24 hours, heating at 120 °C for 90 or 360 minutes. | Akhtari and Arefkhani, 2016 |
| Bagasse fibre (Saccharum officinarum L.)    | Acetic anhydride heating 120 °C for <4 hours.            | Rowell and Keaney, 1991    |
| Beech wood (Gmelina arborea)                 | Acetic anhydride or acetic acid /CaCl$_2$, heating 120 °C for 3 hours. | Azeh et al., 2013          |
| African baobab (Adansonia digitata)          | Acetic anhydride or acetic acid /CaCl$_2$, heating 120 °C for 3 hours. | Azeh et al., 2013          |
| Corsican pine (Pinus nigra)                  | Acetic anhydride/pyridine, vacuum for 1 hour, heating 120 °C. | Hill and Jones, 1996       |
| River red gum (Eucalyptus camaldulensis), Populus spp., white willow (Salix alba) | Acetic anhydride/dimethylacetamide heating at 100 °C for <6 hours. | Ozmen, 2007                |
| European beech (Fagus sylvatica)             | Acetic anhydride vacuum /pressure, heating at 120 °C for 9 hours, drying at 105 °C for 12 hours. | Militz, 1991ab             |
Table 3 (cont.): Summary of selected examples of acetylation.

| Species | Acetylation method | Reference |
|---------|--------------------|-----------|
| European white birch (*Betula pendula*) | Acetic anhydride heating at 110 °C, various time. | Popescu et al., 2014 |
| Obeche (*Triplochiton scleroxylon*) | Impregnation with acetic anhydride, heat 120 °C for 1 – 5 hours. | Adebawo et al., 2019 |
| Dark-bark spruce (*Picea jezoensis*) | Various methods (catalysed and uncatalysed). | Obataya and Minato, 2009 |
| Jute (*Corchorus olitorius*) cloth | Acetic anhydride, heating at 120 °C for 2 hours. | Andersson and Tillman, 1989 |
| Japanese cedar (*Cryptomeria japonica*) | Acetic anhydride/supercritical carbon dioxide at 10 – 12 MPa, heating to target 120 – 130 °C for less than 63 hours. | Matsunaga et al., 2010 |
| Maritime pine (*Pinus pinaster*) | Acetic anhydride heating at 120 °C for 2 hours. | Jebrane et al., 2011 |
| White cedar (*Thuja occidentalis*), sugi (*Cryptomeria japonica*) | Acetic anhydride treatment for 24 hours, heating at 120 °C for 24 hours. | Hadi et al., 2015 |
| Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) | Acetic anhydride, vacuum for 1 hour, impregnation at 10 bar for 1 hour, heating at 120 °C for 6 hours. | Larsson and Simonson, 1994 |
| African oil palm (*Elaeis guineensis*) | Acetic anhydride: xylene 140 °C 4 hours, OR acetic anhydride: toluene 135 °C for 1 hour. | Subagiyo et al., 2017 |
| Rice straw (*Oryza sativa L.*) fibre | Acetic anhydride/ Various catalysts, heating at 100 °C for 0.5 hour. | Sun and Sun, 2002ab |
| Radiata pine (*Pinus radiata*) | Acetic anhydride, vacuum, heating at 110 °C. | Beck et al., 2018 |
| Rubberwood (*Hevea brasiliensis*) | Acetic anhydride/pyridine, heating at 100 °C for less than 27 hours. | Rafidah et al., 2006 |
| Norway spruce, Scots pine | Acetic anhydride, vacuum, impregnation at 10 bar for 2 hours at 20 °C and microwave heating. | Larsson-Brelid and Simonson, 1999 |
| Southern yellow pine | Acetic anhydride, vacuum, heating at 140 °C. | Zelinka et al., 2020 |
| Southern yellow pine, ponderosa pine (*Pinus ponderosa*) | Acetic anhydride/xylene, heating vacuum, oven heating. | Goldstein et al., 1961 |
| Wheat straw (*Triticum aestivum*) | Immersion/drain, 120 °C. Work undertaken at BP chemicals, UK. | Gomez-Bueso et al., 1999 |

Industrial conditions

| Species | Acetylated in the plant of Accsys Technologies in Arnhem, The Netherlands. | Reference |
|---------|-------------------------------------------------|-----------|
| European beech, European alder (*Alnus glutinosa*), lime (*Tilia spp.*), Maple (*Acer spp.*) | | Bollmus et al., 2015 |
| European hornbeam (*Carpinus betulus*) | | Fodor et al., 2017 |
| Norway spruce, Douglas fir (*Pseudotsuga menziesii*) | | Bongers and Uphill, 2019 |
| Radiata pine | | Bongers and Beckers, 2003 |
| Southern yellow pine | | Wålinder et al., 2013 |
| Fibres from European aspen, European beech | | Gomez-Bueso et al., 1999 |

3.2. Furfurylation

Furfuryl alcohol is a liquid produced from agricultural wastes such as sugar cane and corn cobs. Furfurylation is a process in which a material is impregnated with furfuryl alcohol (or its derivative/prepolymer) in the
presence of a mild acid catalyst. This is followed by a heat-curing step and drying including recycling of chemicals, where the heating results in a hard and resistant product. The resin contributes to the dark (brownish) colour of the product but, when exposed to direct solar radiation, greying occurs. The first commercial plant for the furfurylation of wood was the Kebony® AS company which started in 2009 in Skien outside Oslo in Norway (Kebony, 2020). It can produce 20,000 m$^3$/year and another plant has recently been established in Antwerp, Belgium. Foreco Dalsen in The Netherlands also produces furfurylated solid wood products named Nobelwood® (1,000 m$^3$) from radiata pine using pre-polymerised furfuryl alcohol resin (Jones et al., 2019). A review of furfurylation was recently published (Mantanis, 2017).

The polymerisation of furfuryl alcohol in wood is a complex chemical reaction, and the question of whether furfurylation is a distinct chemical process remains unanswered. The furfuryl alcohol reacts with itself forming a polymeric structure and possibly with the lignin in the cell walls (Lande et al., 2008; Nordstierna et al., 2008; Gérardin, 2016; Li et al., 2016). Furfuryl alcohol condenses with itself forming water (Figure 5) and a furan condensed product in which the furan units are held together by methylene bridges, although dimethyl ether bridges are sometimes formed (Lande et al., 2008).

![Figure 5: Reactions during the furfurylation of wood: (a) self-condensation of furfuryl alcohol, forming methylene bridge, and (b) condensation of furfuryl alcohol to phenolic compounds via methylene bridging.](image)

Although furfurylated wood products manufactured today are made from Scots pine and radiata pine, several other wood species have been tasked, such as Southern yellow pine, and broad-leaved woods such as maple (Acer spp.), European beech (Fagus sylvatica), and silver birch (Betula pendula) have also been studied (Lande et al., 2004). A summary of furfurylation treatments of selected wood species is given in Table 4.
3.3. Thermal modification

The use of heat in wood processing has been important in ensuring its suitability for use for a long time. There are a range of different processes involving the heating of wood:

1. Wood drying
2. Thermal modification
3. Heating in the absence of air, i.e. pyrolysis and thermolysis.
4. Heating in the presence of air, i.e. combustion:
   - Complete combustion with full access to oxygen
   - Incomplete combustion when the availability of oxygen access is limited.
The processes involving heat and the typical temperature ranges in which they occur and their effects on individual wood components are shown in Figure 6. An elevated temperature is an important component when wood is to be modified solely with the help of water or moisture, but a temperature above 300 °C is of limited practical value due to the risk of severe degradation of all the main wood constituents, but there are exceptions. The degradation starts or at least becomes identifiable at different temperatures for the different main constituents of wood, the extractives being the most sensitive to a temperature increase due to their low-molecular nature and low boiling point, followed in turn by hemicelluloses, cellulose, and lignin.

The modification of wood by heat without chemical additives and with a limited supply of oxygen to prevent oxidative combustion, i.e., thermal modification, is a generally accepted and commercialised procedure for improving some characteristics of wood (Jones et al., 2019). The idea is to alter the internal chemical composition of the material by exploiting the internal reactivity of the material and the removal of some of its active sites instead of adding reagents capable of interacting with the reactive sites. The changes in the wood during thermal modification are fairly well understood, involving softening and the redistribution of lignin components, the loss of acid groups and cross-linking and repolymerisation that occur to varying degrees depending on the wood species. The process conditions play a significant role in the chemistry which takes place, hydrolysis and catalysis occurring more in closed system processes.

At temperatures between 160 °C and 220 °C (European Committee for Standardization, 2008), the main purpose is to ameliorate material properties, such as to increase the biological durability, to enhance the dimension stability, and also to control the colour changes. Thermal modification has also been applied to reduce resin bleed. The principal effects of heating wood were known already in the early 19th Century. Tredgold (1820) quoted the Encyclopaedia Britannica and states that steaming of wood improves its resistance to white rot, but he referred also to Duhamel du Monceau (1767) stating that steaming and boiling leads to mass loss. Other early examples of wood being thermally modified to improve its resistance to decay are postholes from
Scandinavian Bronze-age buildings, showing concentrations of charcoal indicating that the ends of the posts had been charred (Källander, 2016).

According to the European Committee for Standardization (2008), thermally modified timber is wood in which the composition of the cell-wall material and its physical properties have been modified by exposure to a temperature higher than 160 °C with limited access to oxygen. There are various processes to achieve this, mostly differing in the way they exclude air/oxygen from the system (Navi and Sandberg 2012). A steam or nitrogen atmosphere can be used, or the wood can be immersed in hot oil. Among previous reviews dealing with thermal modification are Rapp (2001), Esteves and Pereira (2009), Pelaez-Samaniego et al. (2013), Candelier et al. (2016), Gérardin (2016), and Sandberg et al. (2017). A summary of recent thermal modification studies into different wood species is given in Table 5.

Table 5: Overview of recent studies into thermal modification.

| Species                          | Temperature (°C) | Duration (hours) | Others                  | Reference                                      |
|----------------------------------|-----------------|-----------------|-------------------------|------------------------------------------------|
| Acacia (Acacia spp.) hybrid      | 210 - 230       | 2 - 6           | Nitrogen                | Tuong and Li, 2011                             |
| Balkan beech (Fagus moesica C.)  | 170, 190, 210   | 4               |                         | Todorović et al., 2015                         |
| Bamboo                           | 130, 180        | 2 or 5          |                         | Nguyen et al., 2012                            |
| Bamboo                           | 130, 220        | 2 or 5          |                         | Bremer et al., 2013                            |
| Black pine (Pinus nigra)         | 140 - 200       | 0.5 – 2         | Coconut oil             | Manalo and Garcia, 2012                        |
| Black spruce (Picea mariana)     | 130, 180, 230   | 2 or 8          |                         | Akyildiz and Ates, 2008                        |
| Calabrian pine (Pinus brutia)    | 130, 180, 230   | 2 or 8          |                         | Lekounougou and Kocaefe, 2014                  |
| Common aspen (Populus tremula)   | 160 - 170       | 1 or 3          | P = 0.65 - 0.76 MPa, steam | Grinins et al., 2013                           |
| Common oak (Quercus spp.)        | 160, 180, 210   | 3               | ThermoWood® process     | Bächle et al., 2010, Majka and Roszyk, 2018    |
| European alder (Alnus glutinosa) | 150, 180, 200   | 2, 6 or 10      |                         | Cai et al., 2020                               |
| European ash (Fraxinus excelsior)| 180, 200        | 3               |                         | Bächle et al., 2010                            |
| European beech (Fagus sylvatica) | 170, 180, 210   | 2               | Steam                  | Kol and Sefil, 2011                            |
| European white birch (Betula      | 160, 190        | 1               | P = 0.78 MPa            | Altermann et al., 2002                         |
| Fir (Abies spp.)                 | 170, 180, 190, 212 | 2            | Vacuum                 | Kol and Sefil, 2011                            |
| Fir (Abies spp.)                 | 160, 220        | 1, 3 or 5       |                         | Allegretti et al., 2012                        |

Jones and Sandberg, 2020
Table 5 (cont.): Overview of recent studies into thermal modification.

| Species                        | Temperature (°C) | Duration (hours) | Others                                | Reference                                      |
|--------------------------------|------------------|------------------|---------------------------------------|------------------------------------------------|
| Flooded gum (Eucalyptus grandis) | 180, 200, 220, 240 | 4 or 8           |                                       | de Cademartori et al., 2013a                   |
|                                | 140, 160, 180     | 45 minutes       | VAP Holzsysteme®                      | Batista et al., 2015; Carvalho et al., 2019    |
| Grey alder (Alnus incana)       | 160 – 170         | 1 or 3           | P = 0.65–0.76 MPa, steam              | Grinins et al., 2013                            |
| Gympie messmate (Eucalyptus cloeziana) | 180, 200, 220, 240 | 4               |                                       | de Cademartori et al., 2013b                    |
| Loblolly pine (Pinus taeda)     | 140, 160, 180     | 45 minutes       | VAP Holzsysteme®                      | Carvalho et al., 2019                          |
| Mantsurian poplar (Populus cathayaba) | 160, 180, 200, 220, 240 | 4   |                                       | Wang et al., 2015                              |
| Maritime pine (Pinus pinaster)  | 170 – 200         | 2 – 24           |                                       | Ling et al., 2016                              |
| Meranti (Shorea spp.)           | 160, 180, 210     | about 3          | ThermoWood® process                   | Gašparik et al., 2019                          |
| Merbau (Intsia spp.)           | 160, 180, 210     | about 3          | ThermoWood® process                   | Ditommaso et al., 2020                         |
| Msasa (Brachystegia spiciformis Benth.) | 215, 230, 245   | 2                | Steam                                | Nhacila et al., 2019                           |
| Narrow-leaved ash (Fraxinus angustifolia) | 160, 180, 200, 220 | 2 or 4          |                                       | Korkut et al., 2012                            |
|                               | 160  – 260        | 2 – 8            | Steam                                | Yalcin and Sahin, 2015                         |
|                               | 195               |                 |                                       | Kotilainen et al., 2008                        |
|                               | 200               | 2, 4, 8, 10 or 24| RH = 50, 65, 80, 95%                  | Bekhta and Niemz, 2003                         |
|                               | 100, 150          | 24               | RH = 50, 65, 80, 95%                  | Folrich et al., 2006                           |
|                               | 200               | 0.08, 0.5 or 1   |                                       | Bächle et al., 2010                            |
|                               | 180, 200, 220     | 4                |                                       | Allegretti et al., 2012                        |
|                               | 160, 220          |                 | Vacuum                               | Kačíková et al., 2013                          |
|                               | 113, 134, 158, 187, 221, 237, 253, 271 | 1.5         |                                       |                                               |
|                               | 160, 180, 210     | 3                | ThermoWood® process                   | Gaff et al., 2019                              |
|                               | 180               | 2                |                                       | Cai et al., 2020                               |
| Oil palm (Elaeis guineensis) mesocarp fibre | 190 – 230       | 1, 2 or 3        |                                       | Nordin et al., 2013                            |
| Oleaster-leaved pear (Pyrus elaeagrifolia) | 160, 180, 200 | 3, 5 or 7       |                                       | Gunduz et al., 2009                            |
| Oriental beech (Fagus orientalis) | 130, 150, 180, 200 | 2, 6, or 10   |                                       | Yildiz et al., 2005                            |
|                               | 150, 160, 170     | 1, 3, 5, or 7    |                                       | Charani et al., 2007                           |
| Paulownia spp.                 | 160, 180, 200     | 3, 5 or 7        |                                       | Kaygin et al., 2009                            |
|                               | 150, 170          | 0.75             | P = 0.20 or 0.225 MPa                 | Candan et al., 2013                            |
| Rubberwood (Hevea brasiliensis) | 210 – 240         | 1 – 8            |                                       | Srinivas and Pandey, 2012                      |
| Red-bud maple (Acer trautvetteri Medw.) | 120, 150, 180 | 2, 6 or 10      |                                       | Korkut et al., 2008a;b; Korkut and Guller, 2008 |
| Red msasa (Brachystegia spiciformis) | 215, 230, 245 | 2                | Steam                               | Nhacila et al., 2019                           |
| Species                | Temperature (°C) | Duration (hours) | Others                          | Reference                     |
|-----------------------|------------------|------------------|--------------------------------|-------------------------------|
| Scots pine (Pinus sylvestris) | 160, 180, 210, 240 | 5                | 0.6                            | Burmester, 1973               |
|                       | 160 - 260        | 2 – 8            |                                | Kotilainen et al., 2008       |
|                       | 120, 150, 180    | 2, 6 or 10       |                                | Korkut et al., 2008a,b        |
|                       | 180, 200, 240    |                  |                                | Kekkonen et al., 2010         |
|                       | 125, 140, 155, 170 | 3                | Superheated steam at atmospheric pressure | Altgen et al., 2020b          |
|                       | 180              | 2                |                                | Cai et al., 2020              |
|                       | 225              | 3                |                                | Willems et al., 2020          |
| Sessile oak (Quercus petraea) | 130, 180, 230    | 2 or 8           |                                | Akyildiz and Ates, 2008       |
|                       | 190, 212         | 1 – 2            | ThermoWood® process            | Gurleyen et al., 2019         |
| Silver oak (Grevillea robusta) | 210 - 240      | 1 – 8            |                                | Srinivas and Pandey, 2012     |
|                       | 185–230          | 2 – 3            |                                | Sikora et al., 2018           |
| Small-leaved lime (Tilia cordata) | 140            | up to 504        | RH = 10 %                       | Popescu et al., 2013a,b, Popescu and Popescu, 2013 |
| Sweet chestnut (Castanea sativa) | 130, 180, 230   | 2 or 8           |                                | Akyildiz and Ates, 2008       |
|                       | 160, 180         | 2 or 4           |                                | Korkut et al., 2012           |
| Teak (Tectona grandis) | 160, 180, 210    | about 3          | ThermoWood® process            | Gašparík et al., 2019         |
| Turkish hazel (Corylus colurna) | 120, 150, 180   | 2, 6 or 10       |                                | Korkut and Hıziroglu, 2009    |
|                       | 195              |                  |                                | Wikberg and Maunu, 2004       |
| Warty birch (Betula pendula) | 140, 160, 180   | 1                |                                | Biziks et al., 2013           |
|                       | 160 - 170        | 1 or 3           | P = 0.65 – 0.76 MPa, steam      | Grinins et al., 2013          |
| Western red cedar (Thuja plicata) | 220             | 1 or 2           |                                | Barci et al., 2015a           |

### 3.4. Impregnation polymerisation

The use of resins for improving the properties of wood is a well-studied procedure, with the development of the Impreg™ and Compreg™ processes during the first half of the 20th Century (Stamm and Seborg, 1943, 1944; Stamm et al., 1946). As the name suggests, the main difference between Impreg™ and Compreg™ is the application of compressive forces before and during the curing process of the latter. An excellent overview of properties of these two products was given by Ibach (2010), which is summarised in Table 6.

Table 6: Comparison of Impreg™ and Compreg™ processed timbers (Ibach, 2010).

| Property                     | Impreg™ | Compreg™                                      |
|------------------------------|---------|------------------------------------------------|
| Density                      | 15 % to 20 % greater than untreated wood | Usually 1,000 to 1,400 kg/m³                       |
| Equilibrium swelling and shrinking | ¼ to ½ that of untreated wood | ¼ to ½ that of untreated wood at right angle to direction of compression, greater in direction of compression but very slow to attain |
| Spring-back                  | None    | Very small when properly made                  |
| Face checking                | Practically eliminated                | Practically eliminated for densities less than 1,300 kg/m³ |
| Grain raising                | Greatly reduced                       | Greatly reduced for uniform-texture woods, considerable for contrasting grain woods |
Typically, Compreg™ is based on phenol-formaldehyde resins, whilst Impreg™ can be based on phenol-, melamine- or urea-based, cured under mild acidic or alkaline conditions, and incorporating a monomer such as methyl methacrylate or styrene, which provide hardening by a stepwise polymerisation mechanism. An overview of the resin modification of wood was reported by Stefanowski et al. (2018).

In addition to the development of Compreg-type products, there have been a range of Impreg-type products manufactured. The commercial production of wood treated with poly(methyl methacrylate) has been carried out since the 1950s. The US company Gammapar commercialised the production of acrylic impregnated parquet flooring in 1963. Grammapar was taken over in 2001 by Nydree, who subsequently in 2003 took over the
product PermaGrain®. Nydree flooring is still sold as an acrylic infused wood is made with superior toughness over untreated products.

The Indurite™ technology was started indirectly via Scion’s Indurite™ development from 1985 to 1988, when a new strategy for wood modification was devised. Patents were granted for the process (Franich and Anderson, 1998), and the Indurite™ technology was scaled-up by the Engineered Wood Solutions company in New Zealand, after which it was obtained by the Osmose company (Franich, 2007). A more traditional resin is now used, the material being produced under a new product brand, Lignia® in the United Kingdom.

Another impregnation/polymerisation process that has gained commercial interest in recent years is the use of 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU) that was used in the early version of the Belmadur® process operated by BASF between 2010 and 2016. This is an example of treatment that has been used in other industrial areas; in this case as an anti-wrinkling agent in cellulose and cellulose-blended fabrics (Schindler and Hauser, 2004). The use of DMDHEU has recently been reviewed (Emmerich et al., 2019). The production of Belmadur® using DMDHEU was stopped in 2016, but Archroma Management GmbH (Reinach, Switzerland) together with the University in Göttingen, Germany, have now resumed investigations to improve the technology using DMDHEU (Emmerich, 2016). Recently, another cross-linking agent (glyoxal) has been advertised by BASF in a process named Belmadur® (BASF 2020). Radiata pine is the preferred species due to the cooperation between TimTechChem International Ltd in Auckland, New Zealand (Emmerich et al., 2019).

4. Wood Modification in Europe

As part of the work in the COST FP1407 Action, it was decided to determine the levels of wood modification across Europe. From earlier work (Militz, 2015), the degrees of commercialisation were reported, as shown in Table 7.

| On the market / commercial production | Ready to be commercialised | Still at research phase |
|---------------------------------------|----------------------------|-------------------------|
| Thermal modification                   | Acetylation                | Chitosan/lignin/tannin  |
|                                       | Furfurylation              | Extractives             |
|                                       | Silicone/silane/water glass| DMDHEU                  |
|                                       | Phenolic resin             | Other chemicals         |
|                                       | Oils/waxes/paraffins       |                         |

An evaluation of the scientific literature (Jones et al., 2019) showed that levels of interest in wood modification were increasing, based on researchers, policy makers and end-users becoming more aware of the importance of the bioeconomy in our future and the need for more environmentally-acceptable treatments. As a result of the activities within COST FP1407 and subsequent overview of all European countries, it was possible to determine more realistic production rates for modified wood, and a better differentiation of modification types on the market, as shown in Table 8 (Jones et al., 2019).

Given that the global production volume from the ThermoWood Association was reported to be 193,700 m³ in 2017 (International ThermoWood Association, 2018), demonstrating how other groups across Europe have expanded into the production of thermally modified timber. This has been aided by the development of small
thermal treatment kilns, such as those produced by IVSE in Italy and Jartek in Finland, with the latter having manufactured more than 50 thermal modification kilns for use globally. Indeed, the national production of thermally modified timber was reported by 27 of the 31 countries that responded to the European questionnaire (Jones et al., 2019). Since the publication of this data, it has been noted that there appears to be an additional 160,000 m$^3$ of thermally modified timber produced by Thermory® in Estonia, demonstrating the regular increases in production levels. Thus, the European production levels of thermally modified timber should be 695,000 m$^3$. The popularity of thermal modification, particularly through its ability to be commercialised on small scales suited to local production facilities, was borne out by the number of European counties reporting some degree of commercial production (Figure 7).

Table 8: Summary of production levels in Europe (including anticipated production from new capacities).

| Type of wood modification | Estimated annual production (m$^3$) |
|---------------------------|-----------------------------------|
| Thermally modified timber incl. aged timber | 535,000 |
| Densified wood | 2,000 |
| Acetylated timber incl. production under development in UK | 120,000 |
| Furfurylated timber incl. production under development in Belgium | 45,000 |
| Other chemical methods | 35,000 |

Figure 7: Production of thermally modified wood in Europe. Red = Production volumes over 10,000 m$^3$/year, Orange = Production volumes under 10,000 m$^3$/year, Green = no reported production volumes, Grey = No data available.
5. Global Wood Modification Position

It is recognised that the European Union has led the development of wood modification in recent years, but opportunities for many of these technologies exist globally, given that the aim of most treatments has been the upgrading of fast-grown (local) softwood species. Indeed, the acetylation (Accoya®) process has to date been based on the use of radiata pine, due to its uniformity and ease of treating. Similarly, species such as poplar and Southern yellow pine have been extensively studied with various modification methods. To date, acetylation and furfurylation remain as European commercial entities, though Eastman Chemicals explored opportunities for the acetylation of Southern yellow pine in the commercial production of Perennial Wood™, though this has ceased production for the current time.

As demonstrated with the European market, it is thermal modification that has been most widely developed globally, again based on the ease of construction of treatment kilns suited to a wide range of production levels. Currently there are several companies in China producing thermally modified timber from species such as Dahurian larch (Larix gmelinii (Rupr.)), Pará rubber tree (Hevea brasiliensis), and Shiny xylosma (Xylosma congestum) as well as plantation-grown poplar spp. and Chinese fir. 2018 estimates indicate there to be a production of around 250,000 cubic metres per year, of which 200,000 cubic metres is classified as a light treatment (from operating temperatures of 140 to 180 °C), with the remainder classified as deep treatment (temperatures used between 180 and 220 °C).

In terms of production levels, the other area where thermal modification has become commercialised to a significant level is in North America. As reported by Espinoza et al. (2015), the estimated production levels of thermally modified timber for 2012 was 100,000 m³. Given the size of the U.S. / North American timber market, this represents a very slow uptake of a new treatment technology suited to upgrading locally grown pine species and historically a result of research and development originating in the U.S. Many of the reasons for this were explained by Morrell (2018), including issues over marketing and product conformity. The need to standardise thermally modified timber within the American codes and standards was recognised through the drafting of a document for the American Wood Preservation Association (AWPA) to overcome the lack of technical data available to specifiers and end-users (Donahue and Winandy, 2014). In Canada, the majority of thermal modification is linked to collaboration with the International ThermoWood Association, particularly through ThermoWood® Canada and Scottywood™ Canada. It is assumed that these two groups account for the majority of the foreign (non-European) production of ThermoWood®, which is estimated at over 30,500 m³ for all non-European countries (17 % of the total global production, Sandberg et al. 2017). Overall, there were several producers of thermally modified wood in Canada and ten in the U.S. in 2012 (Sandberg and Kutnar, 2016).

Thermal modification is not well established in other parts of the globe, with countries such as Australia and South Africa more dependent on preservative treated timber and imported modified timber from current producers in Europe and Asia. New Zealand has some production of thermally modified timber, based on the treatment of locally grown radiata pine. One company, Donelley Sawmillers Ltd, recently doubled its production capacity in 2019 upon the delivery of a second Jartek treatment chamber of 35 m³. In 2017, Abodo expanded its production of thermally modified timber under its trade name Vulcan™ cladding by a further 8,000 m³ a year, whilst Tunnicliffe’s Timber produce ThermoWood® radiata pine, but at an elevated temperature of 230 °C. Thermally modified hardwood timber, under the tradename Truwood™ has been imported into New Zealand by Rosenfeld Kitson for several cladding projects.
As a result of several studies (Batista, 2016, 2018), two commercial facilities have been established in Brazil. Whilst one has only just started production in 2019, the other company (Vale do Cedro - Cedar Valley), produces just over 5,300 m$^3$ per year from plantation species such as *Acrocarpus fraxinifolius*, *Toona ciliata*, *Pinus* spp., and *Tectona grandis*.

Another modification process that has been commercialised globally is the resin impregnation/polymerisation process. In China, this has been undertaken on a range of resin systems, including low molecular weight urea-formaldehyde (UF) resin, phenolic resins and wax. The modification with furfuryl alcohol is also included in the various resin systems being used and it is uncertain if this is using a system similar to the furfurylation processes undertaken in Europe. Hence no attempt has been made to separate production volumes using furfuryl alcohol from other resin systems. Overall, there is a total production of resin impregnated wood in China of 290,000 m$^3$ by six companies, whilst there is the production capacity to more than double this volume should market demands arise. It is known that phenolic resins have been commercially applied to low-density hardwoods in several Asian countries (e.g., Malaysia, India) to produce Compreg™ plywood products. Thus, species such as sesandok (*Endospermum diadenum*), jelutong (*Dyera costulata*), rubberwood (*Hevea brasiliensis*), and mahang (*Macaranga* spp.) among many others have been used to manufacture high-performance products.

Finally, the modification of wood with DMDHEU was previously undertaken in Europe by the BASF Group under the name Belmadur® in the early 2000s. The process has since been licensed to TimTech company in New Zealand, who are developing commercial production under the new tradename HartHolz™.

### 6. Marketing of Modified Wood

The performance of modified wood in various product applications is defined by the Durability Class which the treatment confers on the treated wood and the Use Class as defined by EN 335 (European Committee for Standardization, 2013). A specification manual by the Wood Protection Association in the United Kingdom (WPA, 2011) categorised various product ranges according to typical Use Classes, as shown in Table 1. Based on these definitions, the categorisation of key product groups (WPA, 2011) were proposed. These have been modified herein, comprising the groups as shown in Table 9.

#### Table 9: Product groups and their associated Use Classes (modified from WPA 2012).

| Group | Identifier | Use Classes |
|-------|------------|-------------|
| P1    | Indoor furniture | UC 1 |
| P2    | Floor and non-structural interior uses | UC 1, UC 2 |
| P3    | Exterior joinery | UC 3.1, UC 3.2 |
| P4    | Cladding | UC 3.1, UC 3.2 |
| P5    | Decking | UC 3.1, UC 3.2 |
| P6    | Fencing | UC 3.1, UC 3.2 |
Table 10: Overall estimated global production of modified wood.

| Modification                  | Europe  | China    | N. America | Oceania/Japan | Other |
|------------------------------|---------|----------|------------|---------------|-------|
| Thermally modified timber    | 695,000*| 250,000  | 140,000    | 15,000        | 10,000|
| Densified wood               | 2,000   | <1,000   | 140,000    | 15,000        | 10,000|
| Acetylation                  | 120,000 |          |            |               |       |
| Furfurylation                | 45,000  |          |            |               |       |
| Other methods                | 35,000  | 290,000**|            | 5,000         | TBD** |

* Value adjusted from that in Table 1 (Jones et al. 2019) based on additional data from Estonia.

** Figures are a combination of furfurylation processes other than Kebony® and Nobelwood®, as well as DMDHEU and other resin treatments.

Based on the information within Table 10, it would appear there is a global production volume of 1,608,000 m³ per year, which is dominated by thermal modification. Further increase in production is predicted in the coming years based on consumer needs, licensing of technologies and the relative ease of production of thermally modified timber using stand-alone treatment chambers.

In terms of the application of modified wood, surveys and overviews undertaken by the authors herein indicate that various wood modification treatments can be applied the Use Classes as described in Table 11. The Use Classes where the modified wood products have been commercially demonstrated are marked in green, whilst those in yellow refer to those where studies indicate products may be used.
Table 12: Summary of chemical modification processes and typically used wood species, process parameters, properties and Technology Readiness Level (TRL). T and P are process temperature and pressure, respectively.

| Process | Species used | Process parameters | Properties of the modified wood | TRL scale* |
|---------|--------------|--------------------|---------------------------------|------------|
| Accoya® | Radiata pine | T: <170 °C P: pressurised 2.2 MPa | Improved dimensional stability, durability, low mould resistance, corrosive to fastener | 9 |
| Thermal modification (various) | Norway spruce, Scots pine, various | T: 160 – 230 °C P: various | Improved dimensional stability, moderate durability, reduced mechanical properties | 9 |
| Compreg™ (various) | European beech (veneer) | T: 125 – 150 °C P: 7 MPa | Improved strength (hardness), durability permeability, electric resistance etc., high density | 9 |
| Kebony®, Nobelwood® | Radiata pine, Scots pine | T: <140 °C P: <1.2 MPa | Improved durability, dimensional stability, hardness, corrosion to fasteners, lower toughness | 9 |
| DMDHEU (HartHolz™) | European beech, Scots pine | T: >100 °C P: 1.2 MPa | Improved durability | 8 |
| Organowood® | Norway spruce, Scots pine | T: 20 – 120 °C P: low 1.6 MPa | Stable silver-grey surface, improved durability | 9 |
| Impreg™ (MF) (various) | European beech, Scots pine | T: 60 – 150 °C P: 0.005 – 1.2 MPa | Improved durability, less swelling/shrinking, lower hardness and toughness | 7 |
It is important to note these figures were determined before the COVID19 pandemic, which may impact many of the smaller commercial production sites around the globe. However, there is a demand for high-performance wood products within our modern society and there is still considerable research and the development into improving existing methods and advancing the understanding into emerging technologies. Given the demand for improved products, the market for modified wood is expected to grow further.

ACKNOWLEDGEMENTS

The authors hereby thank the European COST Association for their funding of COST FP1407 and for the information provided by national participants in the initial compilation of data. Support of the CT WOOD—a centre of excellence at Luleå University of Technology supported by the Swedish wood industry—is also gratefully acknowledged.

DISCLAIMER

The authors hereby declare there are no conflicts of interest associated with this article.

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