

Challenges of Wood Modification Process for Plantation *Eucalyptus*: A Review of Australian Setting¹

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ABSTRACT

Australia has significant wood resources in its native forest, but the resource available for harvest becomes lesser due to the conversion of native forest to conservation reserves. The natural occurrences of bushfires, droughts, and cyclones are highly destructive, making the situation worse. The shortage of wood resources is having a significant negative impact on Australia because wood is so scarce that they cannot meet domestic demands, especially durable wood. Australia cleared approximately 100 million hectares of its land to establish forest plantations, and two million trees were planted. However, most of these plantations are for pulpwood production; however, their application for high-value products is limited due to their undesirable properties. Wood modification is a process of improving unfavorable wood properties to be utilized for a wide range of applications. Australia has not adopted any of these modification processes; it still depends on the less toxic wood preservative to treat wood. This study focuses on the recent advancement in industrial wood modification worldwide and how it may be used to modify *Eucalyptus* wood for high-value applications. The opportunities and suggestions for *Eucalyptus* wood modification in Australia will be discussed. Before the study concludes, the future of commercial wood modification for *Eucalyptus* plantation in Australia will also be presented.

Keywords: modified wood, feasibility study, *Eucalyptus*, australia wood industry, plantation wood

1. INTRODUCTION

In 1997, the Australian government announced the 2020 vision in which the forest plantation is targeted to expand to three million hectares by that year. The forest plantation resources intend to become the import replacement to replace imported timber that would benefit the country and support jobs in regional

Australia. It also aims to replace the logs from the native forest with plantation resources so that more forests can be set aside in the conservation reserved (Brown & Beadle 2008). Nonetheless, by 2019, Australia only has an estimated two million hectares of plantation forest with equal percentages of softwoods and hardwoods. The softwood plantations are composed of over 75% *Pinus radiata*, while *Eucalyptus* species dom-

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inate the hardwood plantations. Hardwood plantations in Australia are dominated by *Eucalyptus globulus* (51.1%) and *Eucalyptus nitens* (26.1%) (Downham & Gavran 2019).

Currently, the plantation forest provides 70% of Australia's domestically produced wood products, with the remaining coming from the native forest (ABARES 2018). Softwood saw logs are harvested for domestic use to produce sawn wood for residential construction and furniture manufacturing. They also produce lower-grade pulpwood as a by-product of thinning and final harvest. In contrast, almost all hardwood plantation in Australia is managed for pulp log production.

In Australia, softwood plantation has remained unchanged over the last twenty years, but the hardwood plantation area proliferates at the same period in which tripling in size. While this hardwood resource is still young, the growing supply of plantation hardwood represents an opportunity to increase the wood value beyond log, veneer, pulp, and paper production. Besides, with decreasing log supplies and loss of native forest for forest plantations, there is an increasing interest in developing *E. globulus* and *E. nitens* to produce high-value sawn wood (Tepper, 2007; Beadle *et al.*, 2008). However, since the *Eucalyptus* wood is planted mainly for pulpwood production, these resources have inferior wood properties, such as regular knots, collapse during drying, high radial and tangential shrinkage rate, cracks and/or splits due to growth stresses released during cutting, sawing and drying (Ahmer *et al.*, 2019; Derikvand *et al.*, 2017, Unsal *et al.*, 2011). Hence, researchers are interested in exploring the ability of *Eucalyptus* to be produced as modified wood, for example, densified wood, polymer-impregnated wood, thermally modified wood, and acetylated wood to overcome the low-wood properties. The considerable increase in research on wood modification in Australia in recent years is driven by the uncertain supply of durable wood, the desire to move

away from traditional heavy-metal-based preservatives, and the need to address the unfavourable properties of plantation species.

This review aims to discuss the challenges and opportunities in developing wood modification in Australia for plantation *Eucalyptus*. The main issues addressed in this paper are a) the challenges in adopting wood modification in Australia based on the current commercial modification technologies and relationship with plantation resources in Australia, b) research and development on wood modification in Australia, c) product development of potential wood modification in Australia, and d) the future of industrial wood modification process in Australia. From a broader perspective, this review paper gives an insight into how the challenges in adopting wood modification elsewhere, not only in Australia, can be overcome. A similar situation is happening worldwide with the increasing demand for sustainable high-value products from hardwoods, but the supply is insufficient. Therefore, adopting the wood modification process should be the focus in every country around the world.

1.1. Australian Wood Resources

The increasing interest in using *Eucalyptus* wood to produce high-value sawn wood is due to the decreasing log supplies and loss of native forest for forest plantations (Tepper, 2007; Beadle *et al.*, 2008). However, only 18% of hardwood plantations in Australia manage to produce wood, mainly to supplement the native forest timber production, especially for products like flooring and structural wood. The remaining resources are planted with a short rotation between 12 to 20 years for pulp log production. Nevertheless, the supply of sawlogs from plantations is projected to increase by 2030. For example, Sustainable Timber Tasmania (STT) intends to supply around 150,000 m³ of hardwood sawlogs annually by 2025, and the sup-

ply is enough until 2094 (Wood *et al.*, 2009).

Innes *et al.* (2007) studied the economics of plantation *Eucalyptus* for solid wood products and suggested a few significant findings. Firstly, the value of solid wood from thinned and pruned *E. globulus* logs and logs salvaged from the fibre-managed *E. nitens* is enough for the grower and processor to make a considerable profit. However, the growing and processing of thinned and pruned *E. nitens* were unprofitably caused by the loss of material from internal checking, especially the butt log. There is also a considerable loss in the wood output resulting from the internal check in *E. nitens* and board distortion in *E. globulus*. Thus, the report justifies why the plantation industry players are disinterested in producing solid wood from *Eucalyptus* wood.

Most of the modification process requirements are timber with long and clear length because of the concern with knots that might affect the properties variation and appearance. There is also evidence suggesting that stiffness and strength loss are unreasonably high around knots. Modification process like ThermoWood® and Kebony® utilize wood from self-pruning trees, for instance, *Picea* sp. *Eucalyptus* is commonly self-pruning, but in plantations, it is grown under different conditions causing unfavourable self-pruning. Most of the hardwood plantation resources are managed for fibre in which the stands are unthinned causing the presence of knots on the plantation resources inevitable. Thus, there is a concern of a limited supply of clear wood for continuous feed material if the modification process is adopted (Washusen *et al.*, 2004; Nolan *et al.*, 2005).

1.2. Wood Properties

A wood modification process may affect the wood in a few ways, but the process is often developed according to the wood properties and target end-use (Rowell, 2007). Wood quality is the primary concern for fast-grown plantation wood, especially for solid

wood production. However, in Australia, wood properties that affect the solid wood production from plantation *Eucalyptus* wood are less understood than the resources from native forest *Eucalyptus*. Modified wood seeks to address a broader performance scope other than durability, with dimensional stability in service life as a critical focus. This paper focuses on three critical properties that need to be modified from plantation *Eucalyptus* in Australia: dimensional instability, durability, and fire retardancy.

1.2.1. Dimensional stability

Improving dimensional stability is one of the primary objectives of wood modification, especially in applications with lower moisture risk but with high requirements for exact and constant dimensions, such as for structural materials. In many wood applications, improving dimensional stability will also reduce crack formation, thus keeping the water from the material (Homan and Jorissen, 2004). This is important to retain the durability of the material. The fundamental idea of dimensional stability improvement by wood modification is altering how wood interacts with water (Sargent, 2019).

Dimensional instability is one of the common problems with fast-growing hardwoods (Priadi *et al.*, 2019). Trees that are cut at a younger age have a large portions of sapwood, juvenile wood, and tension wood that have inferior characteristics compared to wood from mature trees (Hadi *et al.*, 2019). Besides, since most of these *Eucalyptus* plantations in Australia are established to supply fibre for pulpwood production, the *Eucalyptus* stands have not been thinned and pruned to maximize the output and reduce cost (Beadle *et al.*, 2009; Nichols *et al.*, 2010). As a result, this timber contains a high percentage of features like knots, limb trace, and gum vein (Derikvand *et al.*, 2017).

Juvenile wood is a plant tissue formed by the immature cambial meristem, and compared to mature

wood, juvenile wood has smaller cells, shorter fibres, thinner cell walls, and higher cellulose microfibrillar angle with lower density, strength, and stiffness (Balboni *et al.*, 2020). The transition from juvenile to mature wood could take around 6 to 15 years or up to 20 years depending on the species, meaning that trees grown in short-rotation plantations contain a high percentage of juvenile wood. In contrast, tension wood occurs due to the bending or leaning of trees in response to environmental stimuli such as wind or light, which cause poor drying performance of the wood, and the stress release of the wood during sawing will cause excessive distortion, splitting, and low sawing accuracy (Washusen *et al.*, 2005).

1.2.2. Durability

Australia's harsh environment and voracious insect life mean most of the timber in the Australian market are either chemically treated or naturally high durability. Durability of timber is defined as the natural resistance to biodeterioration caused by fungi, insects, and mechanical breakdowns like weathering, checking, and splitting. Durable wood is highly desirable for functions unprotected from weather or insect attack, especially termites (Nolan *et al.*, 2005). Termites attack on timber products in Australia is very severe, with subterranean termites being a highly damaging timber pest causing significant damage to the structural timber of buildings in Australia. The attack is so severe that they are known to damage the wall and roofing timbers of a house within three months of construction and cause more destruction to Australia's homes than fire, floods, storms, and tempest, combined.

According to National Construction Code (NCC), wood for structural application must comply with the H3 standard of durability in Australian Standard AS1604. This hazard classifies for outside, above-ground exposure subject to periodic moderate wetting and leaching and moderate decay, borers, and termite attack. In Australia,

only less than 5% of the *Eucalyptus* plantation is planted with high natural durability (class 1 or 2) with a probable in-ground life expectancy of at least 15 years according to Australia Standard 5604 because the main hardwood plantation species in Australia are generally non-durable. *E. nitens* is classified as Class 3 (life expectancy between 7 to 15 years) and Class 4 (life expectancy less than five years) respectively, for above ground and in-ground applications. They are also vulnerable to termites, and their sapwood is susceptible to Lyctid borers. In comparison, *E. globulus* is Class 2 (life expectancy between 15 to 40 years) and Class 3, respectively, for above ground and in-ground applications.

There are several ways wood modification can help to increase wood durability. Firstly, wood modification can lower the moisture content in the wood, in which high moisture content is favourable for the bio-deterioration agent attack. Secondly, the wood modification will increase the dimensional stability of the wood, reducing the possibility of cracks or splits, which would be the insect's entrance. Thirdly, modifying the wood's chemical content by reducing certain chemical content, especially cellulose, that serves as the bio-deterioration agent's food.

1.2.3. Fire resistance

Fire retardant material is vital in Australia as Australia is one of the most bushfire-prone countries. Regardless of the strict precautions and total fire ban days, widespread seasonal grass and bushfires occur frequently. During the 2019-2020 Australian summer bushfires, around 2,000 houses were lost to the fire. The Australian bushfire standard aims to decrease the risk of property destruction due to bushfires or wildfires. It states that the fire-retardant wood should not ignite when exposed to a radiation of 10 kW m⁻² in an oxygen consumption calorimeter. When tested in a cone calorimeter at an irradiance level of 25 kW m⁻², the maximum heat release rate should not be more

than 100 kW m^{-2} , and the average heat release rate for 10 min after ignition should be less than 60 kW m^{-2} .

E. nitens and *E. globulus* are considered slightly combustible (Class 3) in the fire property group number. Therefore, this wood needs to undergo wood modification to increase its fire retardancy approved by NCC to be used in a structural application. Overall, all modification treatment does not improve the fire resistance of the modified wood. However, adding additives, such as boron, can improve the fire performance in ThermoWood[®]. Besides that, there is also a potential to pair other modification processes with fire retardant substances to achieve more excellent fire resistance in wood (Jiang *et al.*, 2014).

2. THE CHALLENGES of WOOD MODIFICATION in AUSTRALIA

There have been industrial operations globally since the 1930s to produce modified wood for niche markets (Hill, 2007; Lahtela *et al.*, 2014). However, none of these processes had received much attention due to the stable supply of durable wood (Esteves and Pereira 2009). Later, in the mid-1990s, there was a rapid growth in the research, development, and adoption of wood modification technologies. It indicates the increasing interest in sustainable products and consumer demand for high performance and low maintenance products. The renewed interest in wood modification technologies is also caused by increasing awareness of the environment's fragility with new technologies developed to increase the wood service life without applying toxic chemicals (Townsend and Solo-Gabriele 2006; Mantanis and Şahin 2017).

Wood modification is a method to enhance wood characteristics to produce a new material that, when discarded at the end of its life cycle, would not cause any environmental hazard higher than the unmodified wood (Hill 2007). The wood properties that can be

improved are dimensional stability, resistance to biological degradation, thermal stability, fire resistance, U.V. resistance, and mechanical characteristics (Rowell 2005). There are three significant types of wood modification process: thermal, chemical, and impregnation modifications. Each modification process has advantages and disadvantages according to the modified wood characteristics and the modification process intricacy (Hill 2011). Thermal modification is useful to improve dimensional stability and durability, and a chemical modification, that is externally applied chemical reagent effectively reduces hygroscopicity. In contrast, impregnation does not alter cell wall polymers' molecular structure but can increase wood density and block water pathways (Ramage *et al.*, 2017).

Currently, there are a few modification processes that are successfully commercialized which are ThermoWood[®], Plato[®] and oil heat treatment (OHT) (thermal modification), Accoya[®] that are originated from the acetylation process (chemical modification) and VisorWood[®] and Kebony[®] that are from the furfurylation process (impregnation modification). Table 1 summarises the origin, output, and methods of the five main commercial wood modifications worldwide.

Despite the interest in modified wood, the total number of modified wood produced globally is still insignificant compared to the conventional treated wood, which is the wood that is treated by using preservatives. Hence, industrial wood modification technologies are still considered embryonic in the wood industry, even after ten to twenty years of commercialization (Dunningham and Sargent, 2015). This can be observed in Australia, whereby the local wood industry is still not moving away from using a heavy metal-based preservative, like copper chromium arsenate (CCA) and other lower toxicity preservatives are considered safe. Militz (2020) suggests other possible reasons for this slow growth of wood modification, including consumer perception, unknown properties,

Table 1. The five primary commercialized wood modification process

Wood modification process	Developer/ country	Application	Process
ThermoWood®	Finnish Research Centre (Esteves and Pereira 2009)	80% are for cladding and decking, internal wall and ceiling panels, and internal flooring (Ala-Viikari and Mayes 2009)	<p>Phase 1: Warming up</p> <ul style="list-style-type: none"> Wood heating and pre-drying in which the kiln temperature is quickly increased and produce steam. <p>Phase 2: Drying</p> <ul style="list-style-type: none"> Temperature is raised gradually, and timber is dry until the moisture content reaches near 0%, and the temperature is increased to 185° - 215°C for 2 - 3 hours, depending on its application. <p>Phase 3: Cooling and conditioning</p> <ul style="list-style-type: none"> The wood temperature is decreased to 80° - 90°C by using water spray systems. Conditioning is carried out to moisten the heat-treated wood between 4 - 7% (Shi <i>et al.</i>, 2007; Gérardin, 2016).
Plato®	Plato BV, Netherlands	Claddings, garden fences and furniture, poles and sheds and in canal linings and jetty (Homan <i>et al.</i> , 2000)	<p>Step 1: Hydrothermolysis process for 4 - 5 hours at 160° - 190°C in humid conditions and above atmospheric pressure.</p> <p>Step 2: Wood drying until 10% equilibrium moisture for 3 - 5 days.</p> <p>Step 3: Reheating the wood at 170° - 190°C for 14 - 16 hours in dry condition.</p> <p>Step 4: Increase the wood equilibrium moisture to normal process conditions. The treatment duration varies according to the species, thickness, shape, and final product. Hot vapour or heated air is used as a heating medium (Militz, 2002; Gérardin, 2016).</p>
Oil heat treatment (OHT)	MENZ HOLZ, Reulbach, Germany	Garden furniture	Hot oil (rapeseed oil, linseed oil, or sunflower oil) is introduced in a closed vessel with green wood and treated for 2 - 4 hours, with 18 hours in total, including the heating and cooling phase (Rapp and Sailer 2000; Gérardin, 2016).
Accoya®	Accsys Technologies, Arnhem, Netherlands	Exterior for window and door, decking, cladding, and civil construction, especially outdoors, above- and in-ground contact (Mantanis, 2017)	The standard procedure is by using acetic anhydride containing a small amount of acetic acid without a catalyst. Heat is applied using microwaves or conventional heating (Rowell, 2006). The reaction of acetic anhydride with wood polymers resulting in the esterification of the free hydroxyl group in the cell wall with the formation of acetic acid as by-products, which are usually eliminated as the human nose is sensitive to its smell and it is highly corrosive to ferrous fastenings (Hill, 2011; Mantanis, 2017).
VisorWood® and Kebony®	Kebony ASA, Norway	Construction materials (Lande <i>et al.</i> , 2008)	<p>Step 1: The treating solutions are mixed in a mixing tank that consists of furfuryl alcohol, inhibitor, buffering agents, surfactants, and water before the solution is pumped into the buffer tanks.</p> <p>Step 2: The wood is vacuum pressure impregnated with the treating solution by a full-cell process with a vacuum step, pressure step, and a short post-vacuum step.</p> <p>Step 3: In-situ polymerization of the chemicals and grafting reactions with the polymeric wood components. The curing chamber is heated with direct-injected steam, in which the temperature depends on the wood species. The chamber worked as a closed system during the curing period except for ventilation at the end of the process.</p> <p>Step 4: Wood drying in kiln-dryer to achieve final moisture content (Mantanis, 2017).</p>

higher price and lack of experience using the new material.

When considering wood modification technologies, it is essential to consider that wood structure and chemistry can be effectively improved and manipulated during the process and consider the limits presented due to anatomical differences between wood species. This review paper considers the challenges in economics, environmental, and barriers to adoption of wood modification technologies.

2.1. Economics

Financial is one of the reasons that were slowing down the commercialization process of wood modification in Australia. Jones (2007) and Militz (2020) outlined the reasons for the inability of wood modification to be commercialized. Among them are too high market entry price, the high investment cost of specialized equipment, incomplete market survey, and insufficient technology.

Thus, it is crucial to review the economics of the readily available commercial wood modification process. The wood modification process can be quickly adopted if the process is considered economically viable, including low cost of plant set-up, operation, and

production. The cost of a wood modification process varies according to the type of wood modification. Table 2 summarises the different plant setup costs, operational and production costs for the leading commercial wood modification.

Jones and Sandberg (2020) reported that the global commercial production of modified wood is dominated by thermal modifications which produces 1,110,000 m³/year. Whereas, acetylation accounts for 120,000 m³/year and furfurylation 45,000 m³/year. Heräjärvi *et al.* (2020) projected the increase in production for ThermoWood® forecast up to 2030. Although the cost for plant set up, the operational and production of modified wood is slightly higher than the conventional wood, it is still profitable to run the modified wood plant due to its high demand and still less supply of modified wood worldwide.

2.2. Environmental issue

It is essential to consider the environmental impact when adopting wood modification. Even though the wood modification aims to produce modified wood that would not cause harm any more significantly than natural wood during its life cycle, the process during the wood modification might be harmful to the health

Table 2. The cost of commercial wood modification

Wood modification process	Plant set up cost	Operational cost	Production cost
ThermoWood®	\$1 million installations (Hill, 2006)	N/A	N/A
Plato®	Capital investment of \$12 - 17 million to set up a plant with a capacity of 75,000 m ³ (Hill, 2006)	24 \$/m ³ (Hill, 2006)	180 \$/m ³ , which is high due to the complicated process (Hill, 2006; Hill, 2011)
Oil heat treatment	Capital investment of \$540,000 for a capacity of 8,500 m ³ /a (Rapp and Sailer, 2000)	75 – 110 \$/m ³ depending on oil loading (Rapp and Sailer, 2000)	320 – 360 \$/m ³ based on costs for untreated timber of 250 \$/m ³ (Rapp and Sailer, 2000)
Acetylated wood	N/A	N/A	Depending on the size of the plant (eg: \$0.32/lb for 8,000 tons/year, \$0.27/lb for 20,000 tons/year, \$0.20/lb for 100,000 tons/year (Rowell, 2007)

Remarks: The cost is according to the valuation done according to the reference cited. N/A data not available.

Table 3. The health and environmental impact of commercial wood modification

Wood modification process	Impact during processing	Impact during the service life
ThemoWood [®]	$\frac{3}{4}$ wood production consumes energy (in terms of electricity, gas, or biomass) since the treatment is based on heat production, and no chemicals are added (Ferreira <i>et al.</i> , 2016).	<ul style="list-style-type: none"> - Fulfil the criteria of M1 (the best quality and emission class) class of Finnish emission classification of building material (Ala-Viikari and Mayes 2009) - Life cycle assessment (LCA) approved for ecological building material considering the production activities and its disposal at the end of the life cycle (Ala-Viikari, 2007)
Plato [®]	The effort for productive energy utilization: <ul style="list-style-type: none"> - A closed and circulated cooling water system - Isolated equipment - Flash unit that makes low pressure steam out of the condensate of medium pressure steam - During winter, heating is done by pumping the condensate of low-pressure steam through radiators 	N/A
Oil heat treatment	Low environmental impact heat is introduced in the treatment system, and smokes from wood can be retrieved, condensed, and purified (Candelier <i>et al.</i> , 2016)	Wood can be recycled without harmful impact on the environment (Candelier <i>et al.</i> , 2016)
Accoya [®]	Low emissions compared to other typical building materials on a cradle-to-gate basis, such as aluminium, steel, PVC, concrete and ceramic tiles. The embodied emission of Accoya [®] are better than sustainably source woods and offer significant improvements against unsustainably sourced materials like plastics and metals (Trueman 2013).	<ul style="list-style-type: none"> - Lower carbon footprint than steel, concrete, and unsustainably source hardwood, and it is competitive in terms of carbon footprint with sustainably source hardwood (Bongers and Uphill 2019) - CO₂ negative LCA over a full life cycle (Mantanis, 2017)
Kebony [®]	Use of furfuryl alcohol obtained from renewable hydrolyzed biomass waste and improvement of the polymerization process (Gérardin 2016)	It is recognized as exempt from the Biocidal Products Directory (BPD), given the absence of active compounds in the process (Jones, 2007).

Remarks: N/A data not available

and environment. Table 3 summarises the effect of commercial wood modification on health and the environment.

Apart from the direct impact of wood modification on the environment, a few other environmental factors should be considered: the risk of leaching and end-of-life of wood that will be further discussed. Most importantly, the management of discarded treated wood products should be considered when evaluated to adopt a wood modification process as part of its LCA.

2.2.1. Risk of leaching

The oil-type modification sometimes oozes the oil

on the surface of the modified wood. It may occur directly after treatment, or more complex leaching may happen in service when it is exposed to sunlight. This concern is best addressed through rigid control of the process, including avoiding over-treatment and adopting post-treatment conditioning methods, such as final vacuum, steaming, and expansion baths. Usually, the volume of oil that leaches out of the wood is negligible, but it can appear significant if it spreads on the water surface. Wood with a visible oily surface should not be used in sensitive environmental conditions or in uses that are likely to engage human contacts like decking and handrails (Archer and Lebow 2006).

Apart from that, wood is one of the primary components of compostable organic products, for example, soil conditioners, compost, and mulches. Australia Standard AS 4454 states that these products should comply with the National Health Standard or local Environmental Protection Authority. The requirements also include that any clean wood waste can be processed if no more than 5% by volume of load contains chemical or organic contaminants (Daian and Ozarska, 2009). This is due to the risk of leaching in surface and groundwater, especially by chemically modified wood (Townsend *et al.*, 2004). Therefore, treated products cannot be re-used in the animal products sector (Daian and Ozarska, 2009).

2.2.2. End-of-life

Modified wood waste should not be more challenging to handle as the modification process does not introduce any environmentally harmful or risky chemicals into the wood. Therefore, if the waste management of modified wood products results in hazardous waste, it is not caused by modification, but other reasons such as surface treatment or adhesives (Heräjärvi *et al.*, 2020). European Parliament has established a guide to prolong the wood's service lifespan after it is approaching its end-of-life. It follows this hierarchy: wood-based products, re-use, recycling, bioenergy, and disposal. However, due to the modified wood characteristics, not all approaches can be applied to modified wood.

Wood products can be re-used either for the same purpose or a less demanding purpose after simple reshaping. Besides, wood damage sometimes occurs in a limited area, but the entire structure is replaced. In return, it will recover the cladding or decking materials in good condition for second-hand markets and recycling (Heräjärvi *et al.*, 2020). Re-use is a desirable option if the secondary use is appropriate for the product or consistent with its original use (Archer and

Lebow 2006).

Even if the wood products are not qualified for further use, they can still be reprocessed as fibrous materials for making new wood-based products in part of the wood's recycling process. Compared to unmodified wood, modified wood characteristics include odour, combustibility and mechanical performance, low equilibrium moisture content, and slow rate of biodegradation. These characteristics are based on the modification treatment applied. Consequently, re-use and recycling of modified wood should be considered separately for each modified wood product category (Heräjärvi *et al.*, 2020).

Next in the hierarchy is bioenergy. If recycling is not possible, wood products can still produce energy through direct combustion or conversion to gaseous or liquid fuel before burning. However, for chemically modified wood, there might be potential problems with air emission and ash generation. Thus, it is not applicable (Townsend *et al.*, 2004).

The last hierarchy is landfilling, which is the least favoured end-of-life scenario but the cheapest option (Archer and Lebow 2006). Nevertheless, landfilling modified wood is restricted in some countries because of concerns regarding the high potential for surface and groundwater contamination. Most landfills have a leachate management system to reduce contamination and accept treated modified wood waste even though it may come with a cost. In Australia, several Australian state governments increase landfill levies to show stricter landfill policies and make the landfilling of waste unaffordable compared to the recycling industry. Therefore, due to the limited end-of-life of modified wood, the development of alternative disposal options is highly encouraged, including cogeneration, construction/demolition facilities, and more reliable recycling programs to extend landfill life (Morrell, 2004).

2.3. Barriers to Adoption

Apart from the previously mentioned challenges to adopt the wood modification process in Australia, there are also several other barriers to implementation. The first barrier is the lack of technical knowledge in the wood modification process to establish a suitable process for the Australia wood industry. Other than that, differences between states in Australia regarding the availability of wood resources, regulatory requirements, appropriate processing systems, and local market needs should be considered and could present a barrier to adoption. Thus, these challenges and barriers can be tackled via feasibility studies or technical investigations to assess the opportunity requirements and market needs.

3. RESEARCH and DEVELOPMENT (R&D) for WOOD MODIFICATION in AUSTRALIA

The wood industry is separated into two main branches: the first and second processing of wood. The first processing comprises forestry, sawmills, board industry, energy conversion, and pulp and paper industry. The second wood processing is part of the sawmilling industry characterized as production-oriented and adds manufacturing value to the sawn timber to fabricate different wood products. The R&D of wood modification is part of the wood product industry, including the processing chain and manufacturing system (Salim and Johansson, 2016).

Innovation has received much attention from the researchers; however, the topic has only been explored briefly for the forest sector. Prior studies on innovation in the forest industry by Hovagaard and Hansen (2004) recognized distinct categories: product, process, and business system innovation. Innovation research in the forest sector is currently expanding, and

the wood industry's innovation is receiving much attention from the researchers (Stendahl *et al.*, 2013). R&D activities in wood modification can be considered a product innovation that is explained as introducing a good service that is new or significantly improved concerning its properties or expected application. There are many ways how R&D could be done many ways, but the three essential steps that could be done to study the wood modification process in Australia are feasibility studies, long-term investigation, and technology comparison.

3.1. Feasibility Studies

Information on products, markets, logistics, and wood resources availability is needed to conduct the feasibility study on wood modification in Australia. It would involve wood industry players and economists to study the business and financial feasibility and engineers for the technical feasibility.

A comprehensive feasibility study can be done on the locally modified wood, but this cannot be done due to Australia's non-existing wood modification process. Therefore, the application of ThermoWood® to Australian-grown *P. radiata* in New Zealand could provide a benchmark to develop a similar wood modification in Australia. However, some specific information is necessary, such as resource availability, consumer demand, market size, estimated prices, and the potential to meet Hazard Class H3 requirements that should be conducted in the Australia setting.

Besides, while developing the design concepts, it should be ranked in terms of potential cost, benefits, and risk. Strength, weakness, opportunities, and threats (SWOT) analysis is an example of a simple analysis that can be made with key findings from the study to discuss and conclude with the recommendation of a feasible process (Bartels, 2011).

3.2. Laboratory Investigations

Laboratory investigations are pilot studies of the modification process on the Australian wood species that can be done on the laboratory scale. A pilot study is important to validate the idea (Pa *et al.*, 2008). An initial pilot study using a smaller sample (1-meter length) would help determine the chosen modification process's characteristics. Process variables might need to be revised during this laboratory test until the optimum, realistic and workable process is achieved to match the characteristic improvement needed. Besides, the pilot test can help assess the likelihood of success and identify the problem with the method (Lee, 2017).

Once the modification process is succeeded on the laboratory scale, a full-scale trial using 2.4 m sample lengths would help verify the processing parameters to achieve the same intended characteristics. Samples at this size also would display if there were any macro-scale effects from the modification. After successfully validating the modification process, an in-depth feasibility study would be conducted to assess the economic and environmental impact of the proposed treatment.

3.3. Technology Comparisons and Transfer

The ability to evaluate the recommended process with real data and settings is vital. This can be done using a technology assessment model, for example, WoodScope that has been developed for the New Zealand setting. The model provides a precise assessment of technology comparisons using data like processing costs such as capital and feedstock cost, product and by-product prices, labour, energy inputs, and other consumable costs like catalyst and solvents (Hill, 2006). A clear understanding of product operations and prices are needed to develop a similar model for modified wood in Australia. Nonetheless, plentiful data for the Australian setting are still unavailable.

Technology transfer is transferring technology from a person or organization that owns or holds it to another. Technology transfer is essential because this could help to accelerate the R&D of a new product. For example, a thermal modified wood that has been perfected by an Estonian company called Thermory is available in Australia from local suppliers like InStyle, Timber Products and Australian Timbers. Instead of directly importing the wood products, the Australian could learn from the Thermory how to successfully treat the wood.

4. PRODUCT DEVELOPMENT for WOOD MODIFICATION in AUSTRALIA

New product development is a significant process but challenging to perform effectively. Thus, most new products or applications are either terminated or fail commercially (Metzner, 2018). Several considerations are required to ensure the success of the implementation and development of wood modification technologies in Australia, including market opportunities, environmental benefits, industry and regulatory structures, and co-operation between companies and marketing aspects.

4.1. Market Opportunities

In the Asia-Pacific region, the market for wood is expected to rise, with demand forecasted in 2020 will be higher than Western Europe's demand. Makowski (2014) outlines the strengths and opportunities for the Australian wood industry (Table 4).

Much focus on market opportunities is controlled by the commodity wood products, with high-value applications those suitable for modified wood products only covering a small part. Nonetheless, modified wood products would be utilized in the built environment for application like cladding, window joinery,

Table 4. strength and opportunities for the Australian wood industry (Makowski, 2014)

Strength	Opportunities
<ul style="list-style-type: none"> - Located in the Asia-Pacific region, which is a significant growth area. - Excellent wood resources and land availability. - Competitive wood price. - The reasonably strong Australian economy. - Well-known industry players with business models and concepts. 	<ul style="list-style-type: none"> - Export for value-added products. - Operate with fully integrated processing using established business models by executing new models to improve the market. - Update facilities to increase asset productivity. - Provide customized export solutions, including the product, marketing, and supply chain.

and other outdoor applications, including commercial decking and other commercial applications. Besides, there would be other potential products such as furniture making. Modified wood would cover these niches by promoting the improvement and modification of anti-bacterial characteristics, anti-scratch, and effortless to clean.

ABARES projected that the demand for wood products is forecast to rise by 30% by 2050, mainly driven by sawn wood demand. Even though there is no data available on the present market for imported and modified wood from Australia, these products will be most suitable for higher-value applications in the built environment, including interiors. However, the application could be more diverse. Certain modified wood materials could compete with natural, durable hardwoods such as *Intsia* sp. and *Tectona grandis* and Australian hardwoods like *E. marginate* and *E. pilularis*.

The construction of dwellings is a significant market for wood products and an essential driver of economic growth in the wood sector. A statistic done by ABARES (2019) shows that the overall total dwelling commencements show an increasing trend over the years, which gives confidence that the market for building materials will also increase in demand. Other activities in building projects are restoration. Modified wood products could be used in residential restoration projects, for example, decking or cladding substitutes and outdoor living spaces.

Currently, the demand for modified wood products

in Australia is indefinite, even though the modified material is imported from other countries. However, there is a tendency for increased user expectations for residential products' performance, including lesser functional and appearance defects like distortion, splitting, checking, and colour change. Whittle *et al.* (2019) assume that current technologies will remain in place; however, innovative products' importance will increase over time. This would provide opportunities for the forestry sector with new products that could change Australia's domestic wood processing industry structure.

4.2. Environmental Benefit

Several environmental benefits for wood modification technologies were discussed before, including lower toxicity, increased service life, fewer maintenance requirements, lower environmental impact, and carbon footprint. Additionally, modified wood is usually sourced from sustainable plantations compared to precious natural forest hardwoods. If the modified wood is locally produced, the transportation distance can be lowered compared to imported hardwoods.

LCA is an environmental impact assessment on a product that includes its use, life, degradation, acidification, and eutrophication. For wood modification, LCA would include inputs, for example, raw materials, energy, chemicals, manufacturing activity, plant construction, and output like waste, emissions, and effluents (Hill, 2006). Currently, LCA is already con-

ducted on modified wood products, and the data are needed in the Environmental Product Declaration (EPDs) for the products to enter European markets. In addition, international standards (ISO 14040, 14044) specify what LCA should be managed. However, the later standard, which is ISO 14025, does not measure the effect of end-of-life disposal and thus, does not consider the environmental significance presented by modified wood products.

Hill and Norton (2014) showed the comparison of adopting LCA and EPD by providing a convincing study for wood products according to the raw material source, long-term ability to sequester carbon, and disposal techniques to extract energy. Currently, two EPDs for modified wood are available for Accoya[®] and Kebony[®] and LCA for ThermoWood[®]. According to the same study, the life span needed to balance the products' environmental impact is 2.5 times higher for Accoya[®] and Kebony[®] than unmodified wood. This should be achievable due to the durability and service life enhancement that the modified wood could accomplish. The evaluation does not comprehend the maintenance cycle that would extend the service life of the modified wood.

Another metric that can attract consumers is the embodied energy in building materials. Consumer nowadays is more interested in "green" building materials that could lower the carbon footprint and environmental impact. Embodied energy can be found in two forms: (1) initial (i.e., the quantity of non-renewable energy used in the production of the material) and (2) recurring (i.e., the amount of energy used to maintain the material during service) (Hill, 2006). However, it is not easy to accurately calculate the embodied energy in a material. In terms of wood products, it includes the energy consumed during growing, managing, harvesting, and transporting wood resources. This led to difficulties in analyzing the same materials and comparing between the different

materials. As consequence, there are no databases of embodied energy for modified wood.

4.3. Regulatory Structures

One of the main issues that should be tackled in Australia is the wood industry players are not interested in replanting their wood after the current rotations are harvested. In return, it would create problems with the shortage of raw materials in the future. The plantation forestry will not be replanted because the current policy, the investment revenues from plantation forestry are sub-optimal. This is due to the price for wood that is unsustainably low, especially for long rotation wood.

Besides, most of the investments in new plantations are from privately funded companies in which these companies are looking for short-term returns on investment from plantation trees grown explicitly under silviculture practices to produce small-diameter pulp logs for paper products that generally only take about 10 - 15-year rotation (Lott and Gooding, 2007). The uncertainties of economic returns for investors if they invest in plantation sawlogs are due to the possible changes in technology, site and environment, pests and diseases, and high cost associated with the extended period. Thus, ABARES applied a pre-tax discount of 7% to all future returns and costs associated with timber plantations and wood processing investment projects. This incentive is one of the many incentives introduced by the government to encourage these private companies to manage plantation wood for longer rotation (Whittle *et al.*, 2019).

Regulatory bodies could help the plantation industry by introducing policies that could support the industry, especially in their efforts to produce renewable and carbon-positive products manufactured from wood. The government can do other support by helping them financially and supporting product development to increase the plantation wood value.

4.4. Co-operation between Companies

In wood modification, a distinct business benefits from working with other companies in the wood modification sector, especially when the challenge is considered too large to be taken care of by a single company. Better knowledge in terms of characteristics and functionality of wood, technology for wood processing, control of raw material, and production flow, and also development of product standards were all suited for broad collaboration. Thus, industry-wide collaboration, particularly large companies' initiative to advocate for the smaller companies, is crucial (Stendahl *et al.*, 2013). This idealistic viewpoint is possible through the ThermoWood® network in Finland, where product development's best interest is placed ahead of individual company domination. Even though some companies within the ThermoWood® association operate significantly more extensive than others, the collective operation's benefits have been proven.

Nowadays, even research in wood modification is no longer performed by a small group of researchers but by a research community worldwide that has grown considerably over the years (Militz, 2020). For example, the International Research Group of Wood Protection has considered the need for a collective approach in marketing and development for wood modification, demonstrating the increasing awareness of many companies in the increasing importance of non-traditional methods to increase timber species' durability. The co-operation between the traditional wood preservation industry and wood modification needs to be repaid by creating a new market of modified wood, not by capturing the market currently held by preserved wood. The interactions between companies that work in wood modification, wood preservation, coating technologies, product manufacturers, and architects will be interactions that will provide insights on technologies to enter today's market. It is a financially un-

sound option to develop a complete chain from wood treatment to the final product for each process; thus, it is better to use each sector's expertise for the overall benefit (Jones, 2007).

4.5. Marketing Aspects

For a new product to successfully progress from idea to product launching, the marketing activities should be an integral and essential part of it (Metzner, 2018). Unfortunately, marketing activity in the wood industry are frequently skipped over and/or poorly executed. Only through a well-planned and orchestrated marketing policy, a product can succeed in today's aggressive marketplace. The main marketing area that should be accessed is (1) identifying the market area, (2) identifying the main competitors, (3) understanding the product, (4) conducting sales pitches, and (5) making a profit.

Several years ago, the wood modification process was considered a replacement for all treatments and alternative materials. This has been re-evaluated to the point that selected wood modification techniques are aimed towards specific markets. Information in Table 5 could represent an insight into the perceived areas where selected wood modification techniques could be successfully applied, and it is also important to realize that the listed modification methods are not the only options. The table should be used to provide an idea into which market modified products should be targeted. Once the product range has been identified, it is necessary to undertake a SWOT analysis. The aim is to rationally evaluate the potential of a product/method within the selected market.

Other than that, using a brand name instead of 'modified wood' represents a significant step forward, providing a more recognizable product. The primary commercial modified wood like ThermoWood®, Accoya®, and Kebony® are all using the brand name. Besides,

Table 5. Overview of perceived market opportunities for modified wood (Westin, 2001)

Type of product range	Suitable wood modification
Garden furniture	Thermally modified wood
Window frames	Acetylated wood
Exterior door and frames	Acetylated wood
Flooring	Several types of modified wood
Wet room and façade panels	Acetylated wood
Building products	Acetylated/thermal modified wood
Automotive/nautical applications	Furfurylated wood
Use by architect/government organizations	Acetylated/thermal modified wood

it provides the perception of a new timber species, recognized as a marketing advantage. The use of a brand name may be further enhanced with strong environmental credentials.

5. THE FUTURE of WOOD MODIFICATION in AUSTRALIA

It is only inevitable that wood modification will continuously be developed in Australia and elsewhere. Australia needs to catch up with the European countries to develop its modification process that is appropriate for its wood resources. However, it has taken several decades for wood modification in Europe to achieve this point, with severe commercial development established in the past 20 to 25 years. Therefore, it is reasonable for the wood industry in Australia and elsewhere to take time to develop its modification process. Nevertheless, suggestions from the existing application should be taken seriously so that Australia's wood industry would work progressively. For example, Australia can learn from their neighbour country, New Zealand, using their developed wood modification process.

The early stage of developing modified wood would require substantial capital, especially in setting up the production plant. It also would take around 5 to 10 years or longer before they become profitable. Thus,

the government needs to play its role in supporting the industry. When the industry starts to make a profit, it is also likely that the modified materials will be widely available and will reduce production costs. In return, it will make the modified wood more affordable for consumers.

Opportunities to expand modification technologies in Australia are very positive as users are growing in demand for products with excellent performance. Simultaneously, the local councils need to consider the environmental footprint, sustainability, and long-term performance of their building, infrastructure, and facilities to encourage green materials. Besides, wood modification technologies are established with consideration and focus on raising local wood species that can perform well at the commodity level into high-value products. Another consideration that will raise the significance of wood modification in Australia is the reduced supply of naturally durable wood locally or imported from developing countries as regulations and agreements are getting strict. It is a well-known fact that the timber supply is declining at a faster rate. Furthermore, with the increasing utilization of *Eucalyptus* plantation wood in Australia, an effort should be taken so that the low-grade plantation wood in Australia can be increased significantly to reduce the dependency on imported wood.

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