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Review Article

Engineering Wood Products from *Eucalyptus* spp.

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Forest covers 4.06 billion hectares (ha) or 31% of the total land area worldwide, where 93% (3.75 billion ha) are natural regenerating forests and the remaining 7% (294 million ha) are planted forests. *Eucalyptus* spp., being one of the most important plantation species, has been planted in 95 countries around the world, and the area of plantation has exceeded 22.57 million ha. In the southern hemisphere, it is a significant industrial fast-growing tree species. These plantations serve as a valuable resource for the timber and fibre-based industries. *Eucalyptus* is the main fibre resource for the pulp and paper industries in developed countries. Timber extracted from the planted eucalyptus trees has long been used for solid wood and its fibres were used for manufacturing medium-density fibreboard. In comparison to most softwood species, *Eucalyptus* timber is reported to have a higher rigidity, making it ideal for manufacturing structural products. Therefore, this paper presents a review and analysis of the recent state of research on the utilisation of planted eucalyptus for engineered wood products (EWPs) manufacturing. This study investigated *Eucalyptus*-based EWPs such as particleboard, fibreboard, oriented strand board, laminated veneer lumber, plywood, glue laminated lumber, and cross-laminated lumber. The feasibility of using planted *Eucalyptus* in the production of EWPs, as well as the challenges encountered, was also discussed.

1. Introduction

According to the Global Forest Resources Assessment (FRA) report published by the Food and Agriculture Organization of the United Nations (FAO) in 2020, the total forests area worldwide is amounted to 4.06 billion hectares (ha), which covers 31% of the total land area [1]. Two broad categories of forests have been identified by FRA, namely, naturally regenerating forests and planted forests. Natural regenerating forests cover around 3.75 billion ha or 93% of the total forest area. Meanwhile, the total area of planted forests globally is estimated to be 294 million ha or 7% of the world forest area. Asia has the largest area of planted forests which amounted to 135.23 million ha, or 46% of the total planted forests area globally, followed by Europe, North and Central America, South America, Africa, and Oceania. Figure 1 displays the increment of the planted forest area in all regions between 1990 and 2020. As of 2020, the total planted forest area was significantly increased by 72% compared to 1990.

Planted forest typically refers to the forest that is primarily made up of trees that have been planted and/or intentionally seeding. Planted forests provide many benefits including traditional timber and fibre production, economic development, and employment in rural areas [2] and have been identified as a key means to fight climate change in the short to medium term, restore degraded land, and maintain sustainable ecosystem functions and services [3–6]. In the context of a broader geographic and economic context, well-managed planted forests can contribute to sustainable development [7]. Planted forests are now also being proposed as a way to reduce harvesting pressure on natural forests [8].

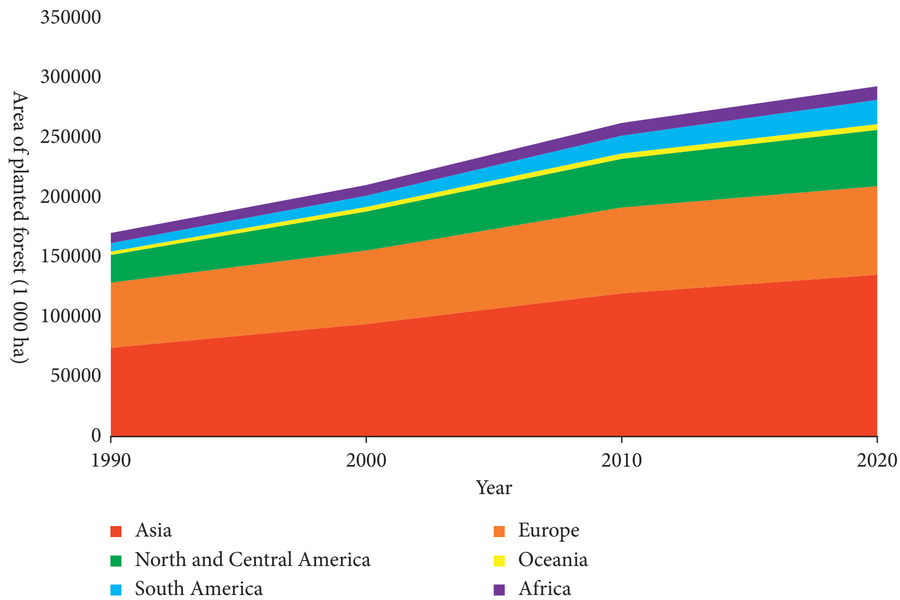

Figure 1: Planted forest area by region for the period 1990–2020 [1].

FRA divided the planted forests into 2 categories: plantation forests and other planted forests. Based on the definitions, plantation forests are intensively managed for productive purposes, with one or two species, even age class, and consistent spacing. Plantation forests are grown for the purpose of producing timber, fibre, energy, and nonwood forest products. A subtype of plantation forests is those primarily made up of introduced species. On the other hand, other planted forests consist of one or more tree species and are less intensively managed, typically for multiple purposes and do not meet the criteria of plantation forests and may even resemble natural forests at stand maturity. The areas of plantation forests and other planted forests by region and subregion are shown in Figure 2. Plantation forests cover 131 million ha worldwide, accounting for 45% of all planted forest land. The remaining 55% is classified as other planted forests, which cover 163 million ha. East Asia has the highest share of plantation forests while other planted forests predominate in Europe [1].

Of all tree species being planted worldwide, *Pinus* species (native and nonnative) are dominant in most regions in the world, while nonnative *Eucalyptus* species are the most common in the tropics and subtropics [9]. *Eucalyptus* is typically managed on short rotation to enhance economy with the production of timber, pulpwood, charcoal, and firewood [10]. *Eucalyptus* is very adaptable, tolerating low soil fertility, acidic soils, and soils rich in aluminium, often periodic moisture stress, diverse climates and soil types, and even fire and insect damages and low water availability [11–15]. Other favourable characteristics of *Eucalyptus* include its good efficiency at capturing CO_2 and producing oxygen, better efficiency in water consumption compared to other species, increasing soil fertility, and restoring land degradation or unproductive land [16, 17].According to Myburg [18] and Iglesias Trabado and Wilstermann [19], currently there are more than 100 countries across six continents around the world planting *Eucalyptus* and covering over 20 million ha, making it the most widely planted broad-leaved tree species worldwide. From 1990 to 2015, the global *Eucalyptus* plantation area increased by 16.57 million ha, with an average annual increase of 1.1 million ha. The ratio of the area of global *Eucalyptus* plantations to planted forests area has also increased from 3.41% to 7.80% within the same period [20]. According to Wen et al., the *Eucalyptus* plantation area in the top 15 countries accounts for nearly 90% of the world's total eucalyptus plantation area. Brazil (22%) has the largest proportion of *Eucalyptus* plantation area in the world, followed by China (20%), India (17%), Australia (4%), Uruguay (3%), Chile (3%), Portugal (3%), Spain (3%), Vietnam (3%), South Africa (3%), Sudan (2%), Thailand (2%), Peru (2%), Argentina (1%), and Pakistan (1%). Although the genus *Eucalyptus* includes more than 700 species and their varieties, those planted for industrial purposes do not surpass a dozen. The "big nine" species (*Eucalyptus camaldulensis*, *E. grandis*, *E. tereticornis*, *E. globulus*, *E. nitens*, *E. urophylla*, *E. saligna*, *E. dunnii*, and *E. pellita*) and their hybrid are dominating 90% of the current *Eucalyptus* plantation [21]. These plantations have the potential to be easily certified with environmental certification schemes such as the Forest Stewardship Council (FSC) if the good forestry practices are followed along the productive chain.

2. Utilization of *Eucalyptus* spp. Fabricating EWPs

Eucalyptus plantations have the potential to be a valuable resource for the timber and fibre industries. However, most countries rely on *Eucalyptus* plantations primarily for low-value applications such as pulp, energy products, or board [22]. Most *Eucalyptus* species are rarely processed into sawn lumber due to the problems related to poor dimensional

Figure 2: Area of plantation forest and other planted forests, by region and subregion, 2020 [1].

stability, regular knots, cell collapse, excessive radial and tangential shrinkage rate, splitting, warp, and brittle heart during processing [23–25]. Splitting, cracking, and warping is most pronounced during the drying process and can be reduced by joining the wood into engineering products or composite components before the drying process [26, 27]. Splitting at the time of logging and warping during milling can be caused also by growth stresses [28, 29]. Growth stresses are often responsible also for brittle heart, especially in large older trees [30]. Most of these problems can be mitigated by applying the heat treatment to *Eucalyptus* logs [31], harvesting young eucalyptus trees, logs sawmill processing, and joining timber into EWPs before drying the wood [24, 32].

2.1. Types of EWPs. EWPs are a type of manufactured composite material made from hardwoods and softwoods. These products are frequently processed to improve their quality and capacity. EWPs comprise a wide range of product types with a variety of manufacturing processes and applications. Particleboard, plywood, fibreboard, oriented strand board (OSB), laminated veneer lumber (LVL), glue laminated timber (GLT), and cross-laminated timber (CLT) are examples of engineered wood products [33] (Figure 3).

Eucalyptus wood could be potentially converted into a wide variety of EWPs. For instance, in the production of hardboard, *Eucalyptus* fibres are preferred. *Eucalyptus* fibres are short, according to Hillis and Brown [34], and thus do not easily form little clumps or masses like lengthy fibres do.

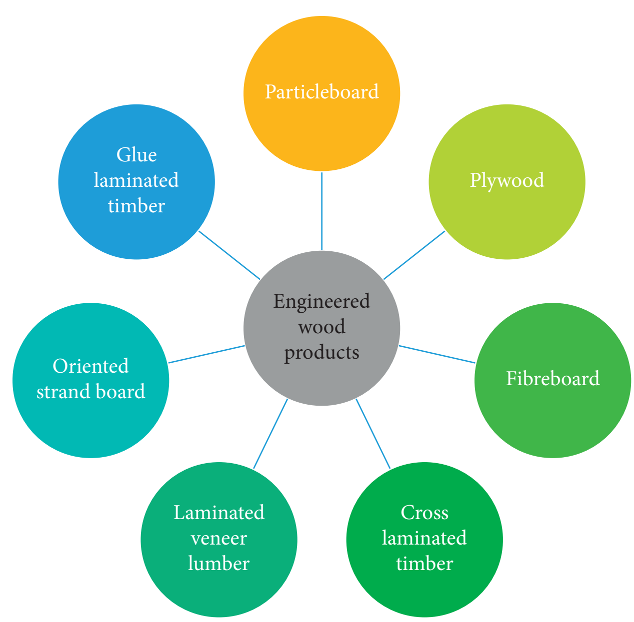

Figure 3: Types of engineered wood products.

As a result, the panels produced are acknowledged to have good surface attributes. Furthermore, when compared to other softwood species, *Eucalyptus* fibres have substantially higher strength qualities. As a result, the boards do not require any additional adhesive to provide the requisite strength. Therefore, this review would mainly focus on the studies reported *Eucalyptus*-based engineered wood products including particleboard, plywood, fibreboards, OSB, LVL, GLT, and CLT.

2.2. Publications on Eucalyptus-Based EWPs. Scopus database was used to search for the publications on EWPs fabricated from *Eucalyptus* spp. wood. The results are displayed in Figure 4.

The most extensively reported EWPs made from eucalyptus are particleboard, which has 127 publications in the Scopus database dating back to 1990. Researchers from Brazil were responsible for over three quarters of the articles. With a total of 100 articles, plywood is the second most widely reported product, with researchers from China and Brazil dominating the field. The production of fibreboard panels derived from eucalyptus wood was covered in 34 publications, whereas the OSB was covered in 20. Between 2012 and 2021, 25 publications on *Eucalyptus*-based CLT were published. Researchers from Brazil, Australia, and China dominated the published data. Between 2003 and 2021, 15 articles on glue laminated wood were found, with Brazilian researchers dominating the published data once again. The only exception is LVL, for which Australian researchers have made the biggest contributions. Since 2013, there have been a total of 18 publications on LVL made from *Eucalyptus*. The increasing numbers of publications over the years reveal that the application of *Eucalyptus* wood in the manufacturing of EWPs has become more and more important. In recent years, CLT is the most widely researched type of EWPs worldwide.

2.3. Particleboard. Several studies have demonstrated the practicality of using *Eucalyptus* species in particleboard manufacture. Da Rosa et al. [35] made particleboards from five eucalyptus species, i.e., *Eucalyptus benthamii*, *E. dunni*, *E. grandis*, *E. saligna*, and *E. urograndis*. As a control, particleboard produced from *Pinus taeda* was used. When compared to particleboard made from *P. taeda*, the results showed that particleboard made from *Eucalyptus* species had a higher modulus of rupture (MOR) and modulus of elasticity (MOE). The particleboard manufactured from *E. grandis* had the greatest MOR and MOE values. Particleboard manufactured from *E. grandis* also had the highest internal bonding (IB) strength. Overall, all of the *Eucalyptus* species met the minimum European EN standard requirements to the MOR and MOE values [36]. Only particleboards manufactured from *E. grandis* and *E. saligna* exceeded the minimum requirement of 18 MPa for MOR when compared to Standard NBR14810-2 (2006) [35]. On the other hand, Rangel et al. [37] employed *E. urophylla* to make particleboard and found that the mechanical qualities of the boards met the German Standards Institute (DIN) and the Venezuelan Industrial Standards Commission's basic standards (COVENIN). In terms of water absorption (WA) and thickness swelling (TS), all *Eucalyptus*-based particleboard had greater dimensional stability than the control, as evidenced by lower WA and TS values.

Figures 5 and 6 display the MOE-density chart and MOR-density chart for particleboard made with *Eucalyptus* spp. and other wood species. From the figures, one can see that the bending strength of the particleboard made of different raw materials does not necessarily follow the trend of strength improved along with increasing density. The findings have been supported by Klimek and Wimmer [47]. However, it does prove that the particleboard manufactured from *Eucalyptus* species has comparable or even better bending strength compared to that of other wood species. Even at lower board density, particleboard made from *Eucalyptus* species displayed better MOE and MOR than that of particleboard made from pine, poplar, and rubber wood.

Niekerk and Pizzi (1994) reported data from studies conducted at a South African particleboard factory which utilised *E. grandis* as raw material and a tannin-based adhesive to produce a moisture-resistant product [48]. The authors outlined two important problems that had to be overcome, i.e., the low pH of the eucalypt furnish, particularly in the high steam environment in the mattress during hot pressing, which inhibited the tannin adhesive curing, and the resistance of the *Eucalyptus* wood particles to crushing during the hot pressing process, which resulted in poor dimensional stability of the fabricated particleboards. Cabral et al. (2007) investigated the properties of particleboards made with particles generated from planer shavings of *E. grandis*, *E. urophylla*, and *E. cloeziana*, bonded with urea-formaldehyde (UF) adhesive [49]. Slash pine *(Pinus elliottii)* particles were mixed with *Eucalyptus* particles to achieve a target panel density of 700 kg.m^{-3}. Overall, particleboards fabricated with the highest proportions of *Eucalyptus* particles demonstrated the highest WA and TS values. Pan et al. (2007) studied the properties of thin particleboard panels fabricated from *E. cinerea*, bonded with polymeric 4,4-diphenylmethane diisocyanate (pMDI) and UF resin [39]. The properties of the panels were compared with those made from *E. camaldulensis*. The authors investigated a wide range of production parameters, i.e., particle size, resin type and addition level, bark content, and hot-water pretreatment. In general, particleboards produced from *E. cinerea* wood particles exhibited significantly better properties than those made from *E. camaldulensis*.

2.4. Fibreboard. Fibreboard is a term used to describe a flat-pressed EWP manufactured from wood fibres obtained by thermomechanical wood pulping and traditionally bonded with a synthetic adhesive. In addition, hardboards represent a flat-pressed EWP composed of randomly oriented wood fibres obtained by thermomechanical wood pulping and bonded without an adhesive by hot pressing by the very high density (900–1100 kg.m^{-3}) and the high-temperature-induced flow of the lignin component of the fibres [50]. *Eucalyptus* has been shown in several researches to be a potential material to produce fibreboard panels. Several *Eucalyptus* species have been reported to be used as feedstocks for medium-density fibreboard (MDF), for example, *E. obliqua*, *E. sieberi*, *E. globoidea*, *E. loxophleba*, and *E. rudis* [51]. Krzysik et al. [52] used *E. saligna* to make medium-density fibreboards (MDF) in three thicknesses (6 mm,

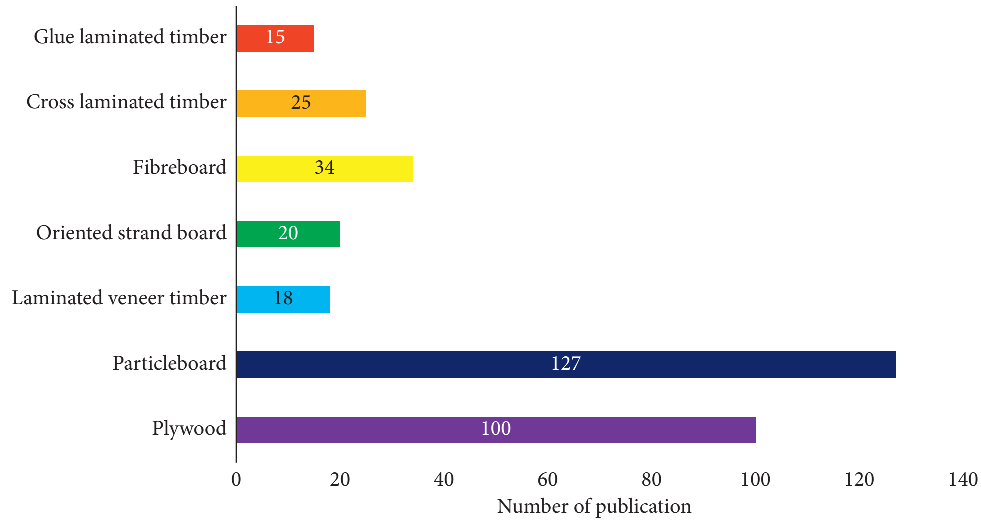

FIGURE 4: Number of publications on EWPs fabricated from *Eucalyptus* spp.

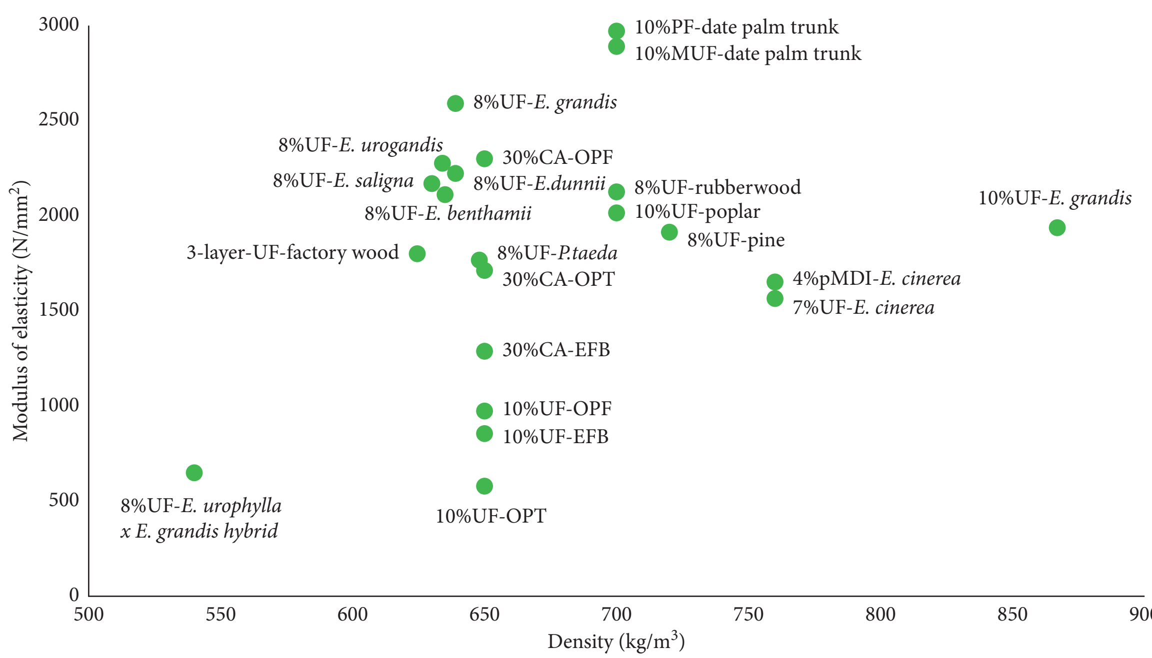

FIGURE 5: MOE-density chart for particleboard made with *Eucalyptus* spp. and other wood species [35, 38–46]. *Note: UF: urea-formaldehyde; PF: phenol-formaldehyde; MUF: melamine-urea-formaldehyde; pMDI: polymeric 4,4-diphenylmethane diisocyanate; CA: citric acid; OPT: oil palm trunk; OPF: oil palm frond; EFB: empty fruit bunch.

13 mm, and 19 mm), bonded with 10% UF resin. The produced MDF was compared to the specifications of the Interior ANSI A208.2 MDF standard [53]. The developed MDF panels exceeded the minimum MOR criteria established by the ANSI A208.2 standard for all three thicknesses examined. The laboratory-fabricated MDF panels of all three thicknesses exceeded the ANSI minimum standard requirements to MOE and IB values. Pranda [54] reported MDF panels fabricated from *E. globulus* and found that the resulting MDF had higher WA and TS than MDF made from *Pinus pinaster*. Furthermore, to achieve comparable mechanical properties, MDF panels made from *E. globulus* required a higher resin amount than MDF made from *P. pinaster*.

Some authors demonstrated the potential of *Eucalyptus* as a feedstock in manufacturing binderless fibreboards. Most of this research is based on the oxidative modification of lignin [55, 56]. Authors in [57] prepared a binderless board from *Eucalyptus grandis* of hydrothermal pretreated *Eucalyptus* wood fibres and characterized it in terms of chemical analyses, mechanical strength, and self-bonding mechanism. The reduction of lignin content of the *Eucalyptus* wood after hot pressing resulted in a decrease in the glass transition temperature and decrease of the softening point of lignin,

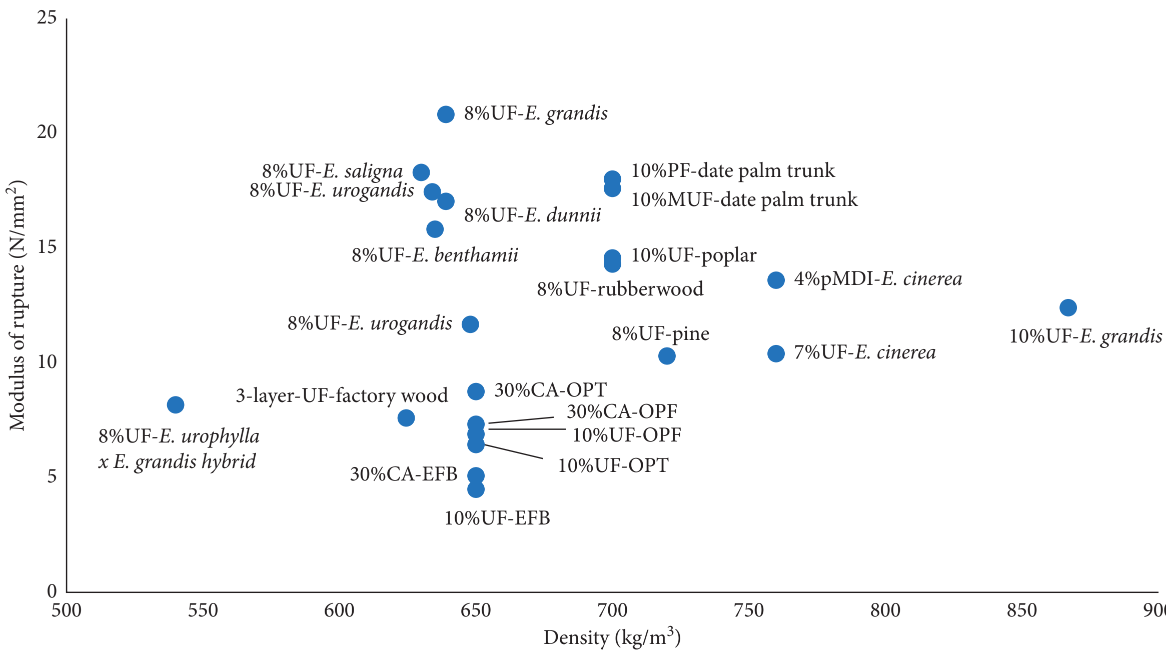

Figure 6: Modulus of rupture- (MOR-)density chart for particleboard made with *Eucalyptus* spp. and other wood species [35, 38–46]. *Note: UF: urea-formaldehyde; PF: phenol-formaldehyde; MUF: melamine-urea-formaldehyde; pMDI: polymeric 4,4-diphenylmethane diisocyanate; CA: citric acid; OPT: oil palm trunk; OPF: oil palm frond; EFB: empty fruit bunch.

which makes lignin more accessible to the fibre surface and plays important role in the self-bonding mechanism [58, 59]. It was explained that high IB value was caused by the intermolecular hydrogen bonding between the cellulose and lignin molecule [60]. In general, it was suggested that the combination of hydrothermal pretreatment and hot pressing process is a good way for conditioning *Eucalyptus* sawdust for the production of binderless boards [61]. Other authors in [62] used Kraft lignin (KL) from *E. globulus* with laccase from *M. thermophila* in a two-component system enabling the manufacturing of MDF panels totally free of synthetic resins or additives, with *E. globulus* as the main raw material. The MDF panels exhibited remarkable high IB and low TS values.

2.5. OSB. OSB is a type of flat-pressed EWP comparable to particleboard that is made by applying thermosetting adhesive resins to layers of wood strands and compressing them. Traditionally, wood from the *Pinus* genus has been used to make OSB [63]. The density of OSB made in the United States is normally between 500 and 800 kg.m^{-3}. The fabrication of panel products, according to Molesmi [64], requires timber with a density of up to 550 kg.m^{-3}. As a result, *Eucalyptus* species could be used to replace *Pinus* spp. wood. As a source of raw materials in the production of OSB, *E. grandis* has been reported as a suitable feedstock for the production of OSB panels [65]. According to the study, using 4.5 and 6% phenol-formaldehyde (MUF) resin is enough to produce OSB panels with mechanical strength complying with the Canadian Standard CSA 0437–0. A study by Domingos and Moura [66] also demonstrated that the *Eucalyptus* bark could be a promising material for the manufacturing of OSB panels.

Following that, several *Eucalyptus* species that are suited for OSB production have been found. Iwakiri et al. [67] used 6% PF resin to make OSB from six different *Eucalyptus* species: *E. grandis*, *E. dunnii*, *E. tereticornis*, *E. saligna*, *E. citriodora*, and *E. maculate*. The OSB panels were produced at a density of 700 kg.m^{-3}. The findings demonstrated that, in terms of physical and mechanical qualities, *E. grandis* and *E. saligna*, particularly *E. grandis*, had a lot of potentials for making OSB. When compared to OSB created from *P. taeda*, OSB made from *E. grandis* had equivalent or superior physical and mechanical properties. The potential of using *E. grandis* and *E. urophylla* as feedstocks in non-oriented and oriented panels was investigated by Gouveia et al. (2000) [68]. The authors concluded that *E. grandis* was the more suitable raw material. In addition, Gouveia et al. (2003) also investigated blends of *E. grandis* and *Pinus elliottii* feedstocks for OSB panels, and optimum results were reported with blends comprised between 50% and 75% *E. grandis* wood [69]. Another study by da Rosa et al. [35] looked at the technical feasibility of using five different *Eucalyptus* species to make OSB. *E. benthamii*, *E. dunni*, *E. grandis*, *E. saligna*, and *E. urograndis* are among the *Eucalyptus* species employed. When compared to OSB panels made from *P. taeda*, OSB fabricated from *Eucalyptus* species demonstrated higher dimensional stability. Furthermore, the MOE value of *Eucalyptus* OSB was higher than that of pine OSB, while there was no significant difference in MOR between the two panels. In comparison to OSB made of pine, the IB strength of OSB manufactured of *Eucalyptus* was shown to be lower. All five species, however, have been identified as suitable for the production of OSB. The practicality of OSB manufactured from *E. grandis* and *E. dunnii* was compared by Iwakiri et al. [70]. OSB was manufactured in two densities: 700 $kg.m^{-3}$ and 1000 $kg.m^{-3}$. OSB produced from *E. grandis* with a density of 700 $kg.m^{-3}$ met the minimum requirements set out in the Canadian and European standards. OSB panels with a higher density of 1000 $kg.m^{-3}$ exhibited greater mechanical strength, allowing them to be used in more demanding load-bearing applications.

2.6. LVL. LVL is a type of EWP that is made up of numerous layers of thin wood that are adhered together. Owing to its uniform engineering properties and dimensional flexibility, LVL is a vital EWP, particularly for the construction of buildings. Several studies have proved that the LVL fabricated from *Eucalyptus* spp. has comparable physical and mechanical properties to that of LVL made of poplar, beech, and even Norway spruce [71, 72]. Large faults can be avoided when logs are cut into thin veneers and assembled and glued parallel to the grain, which may explain why reported LVL values are typically higher than those achieved for other traditional hardwood products [73]. Bal and Bektaş [74] stated that LVL is typically made from softwood species and low- and medium-density hardwood species with densities ranging from 290 to 693 $kg.m^{-3}$. Several studies have found that *Eucalyptus* species are suitable for the generation of LVL. *E. grandis* was used to make LVL in a study by Bal [72], and it was compared to LVL made from poplar. The mechanical properties of *E. grandis* LVL were superior to those of poplar LVL, owing to the higher density of the *E. grandis* veneers. Meanwhile, *E. globoidea* was utilised to make LVL by Guo and Altaner [75]. Unfortunately, despite the high quality and good drying properties of the veneers acquired, the bond performance of the LVL produced is inadequate and does not fulfill The New Zealand standards. Despite some promising results that have been shown, manufacturing of LVL from *Eucalyptus* still encounters some problems such as glue difficulty, end-splits, and breakage of sheets of veneer [76]. Adhesive failure is one of the main issues encountered during the production of *Eucalyptus*-based LVL. However, this issue can be ameliorated by alternating lamination using poplar and *Eucalyptus* veneers as demonstrated by Murata et al. [77]. The authors found the alternating lamination using softer poplar veneers could reduce the quality variations of *Eucalyptus* and hence improved its variation in the modulus of elasticity. Apart from LVL, a new type of structural composite lumber called oriented strand lumber (OSL) has also been developed from *Eucalyptus* spp. Quite similar to that of LVL, OSL is fabricated using strands of wood or strips of veneer with a primary orientation along the length of the member. Chen et al. [78] manufactured oriented oblique strand lumber from *Eucalyptus* wood (*Eucalyptus urophylla* and *E. grandis*) and investigated their mechanical properties. The results revealed that OSL made from *Eucalyptus urophylla* and *E. grandis* had a better compressive and tensile strength in parallel-to-grain direction compared to that of the Sitka spruce, Douglas fir LVL, Spruce-pine-fir (SPF), GLT, and glue laminated bamboo. *Eucalyptus*-based OSL also exhibited higher flexure strength than all of the other wood and bamboo-based products in the study. The study has proven the feasibility of utilizing fast-growing *Eucalyptus* for general use in construction.

2.7. Plywood. The findings reported in the scientific literature on plywood panels manufactured from *Eucalyptus* are presented in Table 1. Most researchers were interested in the effects of species, type of adhesive, and grain direction on the mechanical properties of the plywood panels produced.

Except for the layer configuration, plywood is very similar to LVL. Plywood is made up of thin layers of wood veneer called "plies" that are bonded together with adjacent layers' wood grain rotated up to 90° from one another. For the manufacturing of plywood, Iwakiri et al. [79] used the veneers of nine *Eucalyptus* species. *E. viminalis* was shown to produce the greatest overall outcomes. Meanwhile, *E. phaeotricha* and *E. pellita* veneers had lamination yields of less than 50%. The shear strength of *E. robusta*, *E. dunnii*, and *E. deanei* plywood was not equal to or more than 1.0 MPa. As a result, four *Eucalyptus* species, namely, *E. grandis*, *E. saligna*, *E. globulus*, and *E. viminalis* were recognised as having promising potential for making exterior-use plywood.

E. pellita showed great potential in plywood manufacturing although there are some inferior properties in the veneers. The shear strength and MOR surpassed the minimum requirements. This is supported by the study conducted by Muhammad-Fitri et al. [81]. The authors investigated the effects of layers number and species arrangement on plywood made from batai (*Paraserianthes falcataria*), eucalyptus (*E. pellita*), and *kelempayan* (*Neolamarckia cadamba*). Five and seven layered plywood panels were produced with different species arrangements. For the 5-layer plywood, the arrangement was as follows: BBBBB, KBKBK, KEKEK, and KKKKK. The 7-layer plywood was a repetition of the 5-layer plywood where two more veneer layers were added using a similar sequence as of the 5-layer plywood. The results revealed that plywood made from a combination of *kelempayan* and *Eucalyptus* had significantly higher mechanical strength compared to that of plywood made from *kelempayan* solely especially in the perpendicular direction. The authors attributed it to the higher density of *Eucalyptus* veneers which provide higher strength to the plywood. Bal and Bektaþ [80] studied the effects of timber species regarding their density on the mechanical properties of the plywood produced. The mechanical strength values were divided by their corresponding density to minimize the effect of density. They found out that the specific MOE values of plywood fabricated from eucalyptus veneer were the highest among the other studied timber species. However, the specific MOR only showed a slightly higher value when compared to other species. The authors concluded that *Eucalyptus* wood provided sufficient strength to the final product and was able to enhance the performance of plywood when incorporated with other commercial timber

Table 1: Studies on *Eucalyptus* plywood panels.

Eucalyptus species	Variables	Properties tested and findings	Reference
Eucalyptus grandis, Eucalyptus saligna, Eucalyptus globulus, Eucalyptus viminalis, Eucalyptus dunnii, Eucalyptus robusta, Eucalyptus phaeotricha, Eucalyptus deanei, and *Eucalyptus pellita*	Species parallel and perpendicular to the plane	**MOR (N/mm^2)** 72.23–115.68 (parallel) 39.46–53.43 (perpendicular) **MOE (N/mm^2)** 9378–18494 (parallel) 2738–4627 (perpendicular)	[79]
Eucalyptus grandis *Fagus orientalis* Hybrid poplar *(Populus x euramericana)*	Species *Eucalyptus grandis* (A), *Fagus orientalis* (B), and hybrid poplar (C) Direction of load (parallel and perpendicular) Type of adhesive UF, MUF, and PF	**Specific modulus of rupture (SMOR, N/mm^2)** 12–13 (A, parallel), 6.2–6.7 (A, perpendicular) 12.3–13.1 (B, parallel), 5.4–6.0 (B, perpendicular) 12.5–12.9 (C, parallel), 5.9–6.2 (C, perpendicular) **Specific modulus of elasticity (I, N/mm^2)** 1915–1596 (A, parallel), 477–515 (A, perpendicular) 1242–1273 (B, parallel), 394–403 (B, perpendicular) 1459–1548 (C, parallel), 458–478 (C, perpendicular)	[80]
Paraserianthes falcataria *Neolamarckia cadamba* *Eucalyptus pellita*	Species arrangement Batai (B), *kelempayan*-batai (KB), *kelempayan-Eucalyptus* (KE), and *kelempayan* (K) Number of layers 5 layers, 7 layers Bending (parallel and perpendicular)	**MOR (N/mm^2)** 20.38–40.04 (parallel) 32.39–59.82 (perpendicular) **MOE (N/mm^2)** 2453–4781 (parallel) 2879–6027 (perpendicular)	[81]

species. The research performed by Farrell et al. (2011) was focused on assessing the potential of *E. nitens* and *E. globulus* to produce veneer and plywood. The material studied was comprised of two ages *of E. nitens*, i.e., 16- and 26-year-old and 33-year-old *E. globulus*. All plywood made from the *E. globulus* and the 26-year-old *E. nitens* veneer using phenolic adhesive achieved type A bond quality, while the results for plywood manufactured from the 16-year-old *E. nitens* veneer were variable [82].

2.8. GLT. GLT is a structural EWP made up of layers of dimensional lumber bound together with long-lasting, moisture-resistant structural adhesives. In Europe, there is a growing interest in glued laminated structural products made of hardwoods due to a variety of factors, including a lack of softwoods. In addition, hardwoods are abundant owing to the policies of reafforestation using several hardwood species due to better adaptation to soil and climate conditions. Moreover, in most circumstances, GLT made of hardwoods has higher bending strengths than the highest European softwood GLT strength classes, which are often constructed of spruce or pine [83]. Castro and Paganini [84] used a combination of poplar and Uruguayan *E. grandis* to demonstrate the potential of *Eucalyptus* in making structural glue laminated timber. Castro and Paganini [85] conducted a follow-up investigation in which *E. grandis* of four distinct clones was employed in the manufacturing of glue laminated timber. The glue laminated lumber manufactured from *E. grandis* has shown exceptional mechanical strength and structural efficiency. Apart from *E. grandis*, Tasmanian Oak (*E. regnans/obliqua/delegatensis*) and Blackbutt (*E. pilularis*) have also been glue laminated and their hygroscopic behaviour was examined [86]. Suleimana et al. [87] fabricated glue laminated timber from Portuguese *Eucalyptus* (*E. globulus* Labill.) and concluded that the *E. globulus* is suitable to be used in the production of glue laminated timber. *Eucalyptus* glue laminated timber is suited for structural purposes. In their investigation, Lara-Bocanegra et al. [88] found that glue laminated *E. globulus* timber joined with polyurethane (PUR) adhesive can reach GL45 strength class. If superior solid wood grades were employed, the GL48 strength class may be achieved. It is worth noting that if MUF resin was used to connect the glue laminated timber, strength classifications of GL56 or higher may be achieved. In comparison to the other species, the created *Eucalyptus* glue laminated lumber behaved flawlessly as grid-shells, according to the authors. Petrauski et al. [89] employed glue laminated timber made from *Eucalyptus* sp. to construct porticos. The structures performed admirably and mechanically and demonstrated a high level of technical feasibility in the development of porticos. Carrasco et al. [90] used *E. citriodora* to make glue laminated timber sleepers, and the results were satisfactory, proving the viability of employing *E. citriodora* to make sleepers.

2.9. CLT. Table 2 summarised the findings of *Eucalyptus* CLT panels from various literatures. Most researchers were interested in the effects of species, type of adhesive and primer treatment, strength direction, and timber grade on the mechanical properties of the CLT panels manufactured.

A few *Eucalyptus* species have already been employed in the manufacturing of CLT. According to the literature, the most common resins used to bind CLT are one-component polyurethane adhesive (1C PUR) and MUF resin. Liao et al. (2017) used hybrid *Eucalyptus* wood (*E. urophylla* × *E. grandis*) to make CLT, which they glued with a one-component polyurethane adhesive (1C PUR). They studied the pressing parameters and strength directly on the properties of CLT panels. They found out that the optimal glue spread rate, pressing pressure, and pressing time for the manufacturing of *Eucalyptus* CLT panels were 160 g.m^{-2}, 0.8 N.mm^{-2}, and 200 min, respectively. Mechanical qualities of the resulting CLT panels were comparable to commercially available CLT [96]. Other researchers also concluded that pressing pressure of 0.7 N.mm^{-2} was sufficient to produce CLT panels with sufficient bonding quality without stress grove [94]. Nonetheless, Lu et al. [92] found that using a commercial one-component polyurethane glue led to CLT specimens with lower delamination and shear force resistance compared to commercial softwood CLT. The authors investigated the block shear strength (BSS), wood failure percentage (WFP), and delamination rate (RD) of CLT panels manufactured from hybrid *Eucalyptus* wood (*E. urophylla* × *E. grandis*) using different adhesives and surface primers systems. Four types of adhesives, i.e., epoxy resin (EP), emulsion polymer isocyanate (EPI), phenol resorcinol formaldehyde (PRF), and PUR, were used. Meanwhile, two surface primers, i.e., N, N-dimethylformamide (DMF) and hydroxymethylated resorcinol (HMR), were incorporated. According to the findings, all the adhesives can be utilised to make CLT. Due to its excellent bonding performance and mechanical qualities, CLT bonded with PUR adhesive demonstrated the best properties of all the studied adhesives. The authors also showed that the application of primer can further improve the BSS and WFP of the CLT specimens with HMR primer showing the highest increase in performance. However, RD of CLT showed no significant improvement with the application of surface primer treatment. Therefore, with the suitable adhesive and primer system, the shortcoming of *Eucalyptus* CLT can be overcome. Pangh et al. [93] employed *E. nitens* and *E. globulus* from high-grade and low-grade boards based on their MOE in the production of CLT and discovered that CLT was created from these two eucalyptus species and has better flexural qualities than CLT made from other eucalyptus species. In terms of MOE and MOR, CLT made from *E. globulus* outperformed *E. nitens* between the species evaluated. As expected, the CLT fabricated from high-grade timber board also showed better mechanical performance than their low-grade counterparts. However, the authors found out that the failure mode of the specimens was dependent on the grade of the timber board used. Bending failure on the tensile zone was common among the specimens fabricated from low-grade timber boards while rolling shear failures were observed in the specimens fabricated from high-grade timber boards. Findings from Pereira and Calil [97] also support that *Eucalyptus* wood is an ideal material in the production of CLT as CLT made from *E. urograndis* showed better properties than the CLT made from *Pinus taeda*. Another important aspect of the properties of CLT that needs to be taken into consideration is the rolling shear properties of the transverse layer in the CLT panel. Gui et al. [95] conducted a study to investigate the effect of aspect ratio on the rolling shear properties of CLT made from commercial SPF dimension lumber (spruce-pine-fir) and *E. urograndis*. They concluded that the rolling shear properties of CLT panels fabricated from *Eucalyptus* showed promising results where the rolling shear strength and rolling shear modulus wood were 88% and 260% higher than CLT panels made from SPF lamination.

3. Challenges and Future Perspectives

Even though *Eucalyptus* spp. have shown considerable potential for manufacturing EWPs, various barriers prohibit it from being used more efficiently. The challenges could come from two factors. One factor is the current global trend of the *Eucalyptus* plantation. Another factor is the technical issue of the *Eucalyptus* wood itself. The development of plantation forests is the universal consensus and common action of global climate and ecological governance. Affected by the available forest resources, site conditions, climate change, and public opinion, the development strategies of *Eucalyptus* plantations in countries around the world have undergone major changes. Many countries have altered from encouraging to restricting the development of *Eucalyptus* plantations, making the prospects of *Eucalyptus* plantations uncertain (Wen et al., 2018). According to Wen et al. [20], the future development of *Eucalyptus* plantation is restricted by (i) unsustainable management of eucalyptus plantation under the short-cycle multigeneration continuous planting system, (ii) limited development space of *Eucalyptus* due to shortage of forest land resources, (iii) declining forest stand quality, and (iv) public opinion and the boycott of the development of *Eucalyptus* due to its excessive consumption of soil nutrients and groundwater and negative impact on biodiversity. The high number of growth stresses found in the logs is one of the key challenges. The problem was complicated by the fact that the specific chemical process responsible for the formation of such enormous stresses is still unclear [98]. Processing actions like falling, sawing, and veneer peeling resulted in the production of this growth-stressed substance. As a result, various faults occurred throughout the peeling process, including end-splitting of logs, distortion of sawn boards, and veneer cracking [25]. Worse, these flaws are more visible in plantation species with smaller log diameters. The quality and recovery of *Eucalyptus* veneers were ultimately harmed

Table 2: Studies on CLT made from *Eucalyptus* spp.

Timber species	Variables	Properties tested and findings	Reference
Hybrid *Eucalyptus* wood (*Eucalyptus urophylla* × *E. grandis*	Pressing parameters Glue spread rate (A), pressing pressure (B), and pressing time (C) Strength direction Major strength direction (E0) and minor strength direction (E90)	**Optimal pressing parameter** $A = 160\,\text{g/m}^2$, $B = 0.8\,\text{N/mm}^2$, and $C = 200$ min **MOR (N/mm^2)** 23.8–24.5 (E0) 8.2–9.0 (E90) **MOE (N/mm^2)** 11043–12034 (E0) 661–709 (E90)	[91]
Hybrid *Eucalyptus* wood (*Eucalyptus urophylla* × *E. grandis*	Adhesive Epoxy resin (EP), emulsion polymer isocyanate (EPI), phenol resorcinol formaldehyde (PRF), and polyurethane (PUR) Primer N, N-dimethylformamide (DMF) and hydroxymethylated resorcinol (HMR)	**Delamination rate (RD, %)** 7.6–15.7 CLT bonded with EPI adhesive displayed the highest RD value at 15.7%. Meanwhile, PUR bonded with CLT showed the lowest RD rate at 7.6%. **Block shear strength (BSS, N/mm^2)** 3.01–3.51 (dry state) 1.01–1.62 (wet state) HMR primer increased the BSS values of PRF and PUR bonded with CLT by 31.5% and 4.9%, respectively. **Wood failure percentage (WFP, %)** 73.2–85.6 (dry state) 47.5–58.2 (wet state) HMR primer enhanced the WFP values of *Eucalyptus* CLT at wet state bonded with PRF and PUR adhesives by 27.8% and 12.4%, respectively.	[92]
Eucalyptus nitens and *Eucalyptus globulus*	Species Stress grade of timber	**MOR (N/mm^2)** 41.3–48.6 (*E. nitens*) 56.4–62.7 (*E. globulus*) On average, CLT panels fabricated from *E. globulus* showed 32.5% higher MOR. **MOE (N/mm^2)** 9433–11695 (*E. nitens*) 11250–13610 (*E. globulus*) On average, CLT panels fabricated from *E. globulus* showed 17.7% higher MOE.	[93]
Eucalyptus grandis	Testing method Delamination test EN 16351 (test A), block shear test EN 16361 (test B), block shear test at 45° grain direction (test C), and delamination and shear test at 45° grain direction (test D) Density, grooves, and pressure effect	**Delamination values (%)** 9.7–42.8 (test A) 14.3–58.8 (test D) Higher density and the presence of groove resulted in greater delamination values. In contrast, higher pressure resulted in lower delamination. **Shear strength (N/mm^2)** 3.65–4.96 (test B) 5.08–6.79 (test C) 0.67–2.33 (test D) Higher density and pressure resulted in higher shear strength. In contrast, the presence of grooves resulted in lower shear strength.	[94]
S dimension lumber (spruce-pine-fir) *Eucalyptus urophylla*	Species Aspect ratio	**Rolling shear strength (N/mm^2)** 3.46–3.65 **Rolling shear modulus (N/mm^2)** 375–495	[95]

as a result of these flaws. Only 20% of useable veneers from *E. grandis* were recovered after severe end-splitting, according to Margadant [99]. Unfortunately, no technological solution to this problem has yet been discovered [75]. Apart from faults produced by growth pressures, another issue that needs to be handled is collapse and internal checking during the drying of eucalyptus timber. *Eucalyptus* lumber is difficult to dry due to its limited permeability and the presence of tyloses in the heartwood [100]. Crafford and Wessels [23] found that *E. grandis* has a very high shrinkage and expansion coefficient, with 30% of the *E. grandis* exhibiting warping that did not meet structural lumber specifications. This warping has created challenges in CLT manufacture, where good cross-grain face bonding is essential. According to Ananías et al. [101], drying flaws increased with the increased drying rates and temperatures applied. Even with very slow and cautious drying regimens, the collapse is almost unavoidable.

Despite the aforementioned concerns, various advances have been made to alleviate, if not eliminate, the obstacles associated with effective *Eucalyptus* timber utilisation. Wessels et al. [24] suggested some strategies for addressing the problems, including harvesting *Eucalyptus* trees at a young age, sawmill processing, and green-gluing the lumber into engineered wood products. Green gluing is the method of employing structural adhesive to join green lumber to engineered wood products before the drying process. As the adjacent pieces limit each other, drying-induced splits, cracks, and warping can be reduced. The development of structural adhesive that can be applied to green lumber above the fibre saturation point has made green glued engineered items viable. In the meanwhile, choosing the wood based on its radial placement inside the stem is critical for preventing drying-induced collapse. Wood recovered from the central region of eucalyptus lumber is less prone to collapse, according to Ananías et al. [101] than wood extracted from the transition zone between the centre and the periphery. As a result, while the negative effects of growth stresses and the drying process cannot be eradicated, they can be managed with the right processing approach.

Further research works on the potential of using *Eucalyptus* spp. for manufacturing EWPs should be focused primarily on optimising tree breeding and improving silvicultural practices, e.g., breeding for optimum density and pruning to reduce the wood defects. This would potentially result in enhanced opportunities for wider utilisation of the *Eucalyptus* spp. wood as a promising feedstock for manufacturing EWPs.

Disclosure

A preprint version of this manuscript is available at https://www.researchgate.net/publication/357127148_Engineering_Wood_Products_from_Eucalyptus_spp_A_Review [102].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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