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REVIEW ARTICLE

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Assessment of the properties, utilization, and preservation of rubberwood (*Hevea brasiliensis*): a case study in Malaysia

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Abstract Rubber trees were introduced into the Malay Peninsula more than a century ago. The normal economical lifespan of a rubber tree is about 25 years, and, traditionally, rubberwood was used as firewood by the rural community. In recent decades, rubberwood has become an important timber for wood products, particularly in the furniture manufacturing sector, due to its attractive features, cream color, and good working properties. Sapstain, mold, and wood-decaying fungi are serious threats to rubberwood. Conventional chemical control has been a successful method of preventing staining fungal growth, but the effects of these chemicals are of concern because they create problems for the environment and public health. Thus, biological control has been recognized as an alternative approach to the problem. This article reviews the properties, potential utilization, and problems of protecting rubberwood against sapstain, mold, and wood-decaying fungi, and discusses the treatment methods available. Advances in biological control, particularly biofungicides, are emphasized as an alternative method for rubberwood treatment.

Key words Rubberwood · Molds · Preservation

Introduction

Rubber trees (*Hevea brasiliensis*), indigenous to the Amazon Valley of South America, were introduced to India in the latter half of the nineteenth century.[1] They are now widely cultivated in 20 countries around the world, including Malaysia, for natural rubber and wood panel production.[2] In Malaysia, there are three major agencies responsible for the organization of smallholdings: the Rubber Industry Smallholder Development Authority (RISDA), the Federal Land Development Authority (FELDA), and the Federal Land Consolidation and Rehabilitation Authority (FELCRA). In 1990 about 940 000 ha of smallholdings were managed by these agencies and about 240 000 ha were individually owned.[3]

In rubberwood, there is no distinction between the sapwood and the heartwood.[4] It was considered that rubberwood contains only sapwood,[5] and similar to the sapwoods of all timbers, is nondurable.[6,7] The timber appears to be even less durable than bamboo or oil palm (*Elaeis guineensis*) stems.[8] The attractive features of rubberwood are its creamy color and good woodworking properties.[4] This has prompted many industries to use rubberwood as a substitute for highly priced ramin timber. In fact, rubberwood has carved a niche for itself and has become the timber used in many wood products.[9]

Rubber trees are replanted every 25–30 years when they are uneconomical for latex production.[10] Previous to the utilization of rubberwood for timber and timber-based products, the felled trees were used as fuelwood. However, in the late 1970s, Malaysia started the commercial utilization of rubberwood, such as industries that consume fuelwood (e.g., drying and smoking of sheet-rubber, tobacco curing, and brick making), the charcoal industry, and the blockboard industry.[11] Nowadays, rubberwood can be used for making a wide range of products, such as rubberwood-based panels (e.g., particle board, plywood, medium-density fiberboard), furniture and joinery products, floor tiles and parquet, and moldings.[12–14]

Rubberwood is also very prone to attacks by fungi and wood borers in green and dry conditions.[15] According to George,[16] staining fungi can seriously attack rubberwood as soon as within 1 day of felling. An example is *Botryodiplodia theobromae*, which occurs together with the surface mold *Aspergillus* sp. *Penicillium* spp. also cause considerable loss of strength in rubberwood. Apart from this, wood-rotting fungi such as *Lenzites palisotii* and *Ganoderma applanatum* can also rapidly destroy rubberwood. As

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reported by a few researchers, the high carbohydrate (e.g., sugar and starch) reserves deposited in the parenchyma are major factors governing the high decay susceptibility of rubberwood. In view of the high severity of the decay problem, there is a need for prompt preservative treatment against the attack of biodeteriorating organisms.[17,18]

Boron and copper–chromium–arsenic (CCA) have been reported as important compounds in rubberwood preservation.[19,20] Boron compounds are odorless and relatively less toxic compared with some other preservatives (e.g., lindane) that can pose serious health hazards to the workers performing the treatment and processing of treated timber. CCA-treated rubberwood is rarely used, however, because of the unnatural color of the treated wood. If the timber will be used for construction or structural purposes, it is best to treat the wood with CCA to ensure resistance against biodeteriorating organisms.[21] However, these compounds are becoming less popular nowadays because they are toxic and hazardous to humans.[22] In fact, the persistent use of this chemical is of environmental concern at present and has resulted in the need to search for an alternative approach to rubberwood preservation, especially one utilizing natural resources.

Rubberwood in Malaysia

Rubber plantation revenue

The rubber tree (*H. brasiliensis*), which belongs to the family Euphorbiaceae, is indigenous to the Amazon forests of Brazil and represents the major source of natural rubber in the world.[23] In 1877, nine seedlings of para-rubber were planted behind the house of the British resident Sir Hugh Low in Kuala Kangsar, Perak, Peninsular Malaysia, and these are believed to be the oldest rubber trees in Malaysia.[24] In the 1980s, the Rubber Research Institute of Malaysia (RRIM) sent a delegation to Brazil to source more materials to widen its clonal stock for breeding purposes.[11] There are more than 20 clones of rubber trees planted in Malaysia.[11] For almost nine decades, the Malaysian Rubber Board carried out systematic breeding and selection work on rubber clones from a total of 185 clones in order to improve productivity.[25]

Initially, rubber trees were extensively grown for the production of natural rubber. Akhter[2] showed that latex could be collected economically from a rubber tree for 25–30 years, with its production decreasing gradually; a considerable quantity of rubberwood is obtained during replantation. Mature rubber trees are about 25–30 m tall with an average girth of greater than 1 m at breast height. The trees in Malaysian rubber plantations are much smaller in size and have been bred for the production of latex without considering the volume of wood produced.[11]

In 1991, the total area planted with rubber trees in Malaysia[3] was reported to be 1 820 000 ha. However, the area of rubber trees under cultivation by estates and small holdings in Malaysia decrease from the 1 389 000 ha in 2001 to 1 021 000 ha in the year 2009 (Table 1), a 26.4% decrease in the total area of rubber cultivation in Malaysia.[10,25] This might have resulted from some estates converting to more profitable commodities such as oil palm. However, the future demand for rubberwood is expected to grow, particularly with the scarcity of indigenous timber species.[3] Thus the criteria for breeding of rubber trees will in the future include those for production of wood in addition to latex.[4,26] Another factor that promotes rubber tree replanting is the market price of rubberwood. Smallholders of rubber plantations will demand the highest price possible, as rubber trees are worth RM1000–4000/m^3, depending on the quality and quantity of rubberwood as well as the locality of the holdings.[27] Taking the economic life of rubber trees as 25 years, Yahaya[27] estimated that rubberwood production could be up to 3 207 000 m^3 in 2012, of which 581 000 m^3 (18.12%) would be from estates and 2 626 000 m^3 (81.88%) would be from smallholdings.

Table 1. Total rubber trees planted in Malaysia from 2001 to 2009[10,25]

Year	Estates ($\times 10^5$ ha)	Small holdings ($\times 10^5$ ha)	Grand total ($\times 10^5$ ha)
2001	0.96	12.94	13.89
2002	0.85	12.64	13.49
2003	0.78	12.47	13.26
2004	0.64	12.14	12.79
2005	0.57	12.14	12.71
2006	0.54	12.09	12.64
2007	0.53	11.95	12.48
2008	0.61	11.86	12.47
2009	0.61	9.60	10.21

Table 2. Planted area of rubber trees in Peninsular Malaysia, Sabah, and Sarawak from 2001 to 2009[25]

Year	Peninsular Malaysia ($\times 10^5$ ha)	Sabah ($\times 10^5$ ha)	Sarawak ($\times 10^5$ ha)
2001	11.52	0.87	1.50
2002	11.39	0.63	1.47
2003	11.05	0.64	1.57
2004	10.57	0.65	1.57
2005	10.49	0.65	1.57
2006	10.43	0.65	1.57
2007	10.20	0.71	1.57
2008	10.19	0.71	1.57
2009	7.93	0.71	1.57

There is a slight difference in the rubber tree plantation areas among the different parts of Malaysia (Table 2). From 2007 to 2009, the total planted area in Peninsular Malaysia decreased by 22.25%, while in Sabah and Sarawak the total planted area remained stable. This might be due to availability of large tracts of land which are suitable for commercial agriculture in East Malaysia (Sabah and Sarawak). In fact, to overcome the declining areas of plantation, management of sustainable forest plantation was also practiced. In tandem with the development, additional new planting areas of 0.25 billion m^2 in Sabah and 0.05 billion m^2 in Sarawak, established by government agencies under the Ninth Malaysia Plan, were reported to enable additional production of rubber and rubberwood.[28] This stabilized the plantation areas from 2007 to 2009.

Potential characteristics of rubberwood

Rubberwood (*H. brasiliensis*), like any other wood, is a lignocellulosic material, non-homogeneous in nature and orthotopic in structure. Its density is not uniform and its mechanical properties vary longitudinally, radially, and tangentially.[29] After 25 years, rubber trees normally have clear boles 3 to 10 m in height and a diameter of up to 50 cm at breast height.[30] The structural elements within rubberwood consist of 61.5% fibers, 9.5% vessels, and 29.0% parenchyma cells. The fiber length varies from 1.10 to 1.78 mm, the fiber width is from 26 to 30 μm, and the cell wall thickness is from 5.1 to 7.0 μm. The wood is fine, straight-grained, and light yellowish to white in color, similar to the civit (*Swintonia floribunda*) or champa (*Michelia champaca*), with an approximate specific gravity of 0.56.[31]

The bending properties, compressive and shear strength, and hardness of the rubberwood, as shown in Table 2, indicate that it has good overall woodworking and machining qualities for sawing, boring, turning, nailing, and glaring. In addition, its strength and mechanical properties are also suitable for use in furniture making.[26,29] According to Hong[26] and Killmann,[32] timber with an air-dry density of 560–650 kg/m^3 is classified as medium-dense timber. As can be seen in Table 3, rubberwood (under air-dry seasoning conditions) has a density of 640 kgm^{-3}, which falls into the medium-dense timber category. Air-dried rubberwood, with a moisture content of 17.2%, had higher modulus of rupture (MOR) and modulus of elasticity (MOE) values at 66 N/mm^2 and 9240 N/mm^2, respectively, than green wood.[29] In addition, this medium-dense timber is suitable for wide application as it can be easily steam bent or stained to resemble any other timber.[33,34]

Table 4 shows the comparative mean strength properties of rubberwood at different ages for the clone PB 260. The specific gravity increased with increasing tree age. This is in agreement with studies carried out by previous researchers,[30,35] who stated that the specific gravity of the same clone (PB 260) tends to increase slightly with age. On the other hand, the MOR, MOE and the compression parallel to grain for this clone were not significantly different for different age groups, whereas the hardness, shear parallel to the grain, and the cleavage were significantly different at the 95% confidence limit between the different age groups. Nevertheless, the overall strength properties were higher in the older than in the younger trees for rubberwood clone PB 260, thus indicating that the old trees are more hardy.

Fresh, sawn rubberwood is white to creamy in color, sometimes having a pinkish tinge and weathering to a light straw or light brown color.[4,30] The natural color of rubberwood is one of the principal reasons why it is popular in Japan. All colors are distributed in a sphere known as the color solid. This is represented by a set of three coordinates, as shown in Table 5 for rubberwood and a range of 60 common Malaysian timbers.[35] Whitish wood is often preferred in many applications because it gives a clean and fresh impression, and the wood can be easily stained using dye or pigment.[36] Thus, rubberwood is increasingly used to replace more traditional timber (e.g., *Fagus* spp. and *Quercus* spp.) in a wide variety of applications. As a result, rubberwood has become a good substitute for ramin (*Gonystylus bancanus* Baill) due to its favorable qualities and light color.[4] Another added advantage of rubberwood is its good dimensional stability; its shrinkage or swelling rate is lower compared with that of other tropical species.[37] Extensive research and aggressive marketing have contributed to making rubberwood one of the most important export

Table 3. Physical and mechanical properties of rubberwood[29]

Properties	Seasoning condition	
	Green	Air dry
Moisture content (%)	52.0	17.2
Specific gravity (based on oven-dried weight and volume at test)	0.53	0.55
Density (kg/m^3)	800	640
Static bending		
Modulus of rupture, MOR (N/mm^2)	58	66
Modulus of elasticity, MOE (N/mm^2)	8800	9240
Comparison parallel to grain		
Maximum crushing strength (N/mm^2)	25.3	32.3
Comparison perpendicular to grain		
Stress at limit of proportionality (N/mm^2)	3.65	4.69
Side hardness		
Load to embed a 11.28-mm diameter steel sphere to one half its diameter (N)	3030	4320
Shear parallel to grain		
Maximum shearing strength (N/mm^2)	9.0	11.0

Table 4. Compressive strength properties of rubberwood clone PB 260 at different ages[29]

Property	Age group			Scheffe's Test
	3 years	8 years	14 years	
Moisture content (%)	13.63 ± 1.18	15.30 ± 0.66	14.58 ± 1.67	n.s.
Specify gravity	0.56 ± 0.02	0.57 ± 0.03	0.58 ± 0.02	n.s.
Modulus of rupture, MOR (N/mm^2)	81.01 ± 5.00	84.74 ± 9.65	81.28 ± 5.70	n.s.
Modulus of elasticity, MOE (N/mm^2)	370 ± 810	8534 ± 872	8564 ± 1337	n.s.
Compression parallel to grain (N/mm^2)	33.04 ± 2.13	33.19 ± 4.21	33.55 ± 2.67	n.s.
Hardness (N)	3849 ± 258	4265 ± 505	4187 ± 226	s
Shear parallel to grain (N/mm^2)	11.46 ± 0.62	13.19 ± 1.41	12.48 ± 0.93	s
Cleavage (N/mm width)	12.57 ± 1.29	14.16 ± 2.11	14.47 ± 1.45	s

Data are means ± SDs

s, significantly different at 95% confidence limit by Scheffe's test; n.s., not significant

Table 5. The color coordinates of rubberwood and the ranges of these coordinates for 60 common Malaysian timbers[35]

	Munsell specification system			L*a*b* specification system		
	Hue	Value	Chroma	L*	a*	b*
Rubberwood	9.4YR	7.3	3.0	74.36	3.84	19.00
Range for 60 common Malaysian timbers	1.4Y–0.4YR	3.8–7.7	2.3–5.4	38.69–77.95	2.61–18.08	12.95–29.86

Y, yellow; YR, yellow–red

Table 6. Export value contribution of the Malaysian rubberwood subsector from 2005 to 2009[25]

Product	Export value contribution of rubberwood (RM million)					
	2005	2006	2007	2008	2009	2010[a]
Sawn timber	386.2	69.8	55.2	27.1	34.3	16.8
Furniture	4665.3	5127.4	5331.9	5536.9	4998.6	1291.5
Moldings	698.1	796.3	915.3	744.1	686.4	170.5
MDF	1106.7	1144.9	1180.9	1156.1	1033.4	289.2
Chipboard	266.7	266.9	364.9	391.7	250.9	66.5
Builders' carpentry and joinery	116.1	102.7	101.8	100.5	98.8	22.4
Wooden frames	12.7	12.2	13.2	12.4	16.2	2.9
Total	7251.8	7520.2	7963.2	7968.8	7117.8	1859.8

[a] January to June
MDF, medium-density fiberboard

timbers and a substitute for light tropical hardwoods in the production of furniture and indoor building components.

Fresh rubberwood contains 1.0%–2.3% free sugars and 7.5%–10.2% starch, making it nondurable[37] and easily attacked by fungi and insects. The free carbohydrate content has also created other problems in terms of the setting of cement in cement-bonded panels manufactured in Malaysia.[38] However, this problem may be resolved by open-air storage of the chips, which reduces sugar and starch levels to 0.2% and 1.0%, respectively.[4]

Development strategies of the rubberwood industry

Rubberwood-based industry

In the past 25 years, rubber trees have been planted for latex and timber purposes, particularly in Peninsular Malaysia, and the finished products of rubberwood have captured a lucrative export market. Currently, the Malaysian rubber industry produces a broad range of products from natural rubber to rubberwood-based products. For example, rubberwood has been established as a major wood product in several countries, particularly for the production of furniture, furniture components, and wood panel products, as well as for construction and decorative use.[39] In fact, a strong demand for rubberwood was based on sawn timber, which was reflected in the increase in exports from 95 700 m^3 in 1984, valued at RM29 million, to about 221 000 m^3, valued at RM98.7 million, in 1989, which is an increase of approximately 98% by value.[26] As reported by Chan et al.,[40] in 2004 the rubber products sector contributed RM19.6 billion to the country's export earnings, of which rubberwood products comprised RM6.5 billion. Table 6 shows the export value contributed by the Malaysian rubberwood sector from 2005 to 2009.[35]

Due to this demand, in addition to new mills established solely for rubberwood processing, a number of traditional sawmills have converted to sawing exclusively rubberwood to maintain production capacity and minimize running cost. In 1993, there were 116 stationary and 26 mobile sawmills that processed only rubberwood.[4,32] However, in 1994 there were more than 150 sawmills that processed only rubberwood.[26] Meanwhile, there were a number of mobile mills that operated in plantations and smallholdings. Rubberwood has become popular for use in several wood panel products. In 1999, Malaysia had medium-density fiberboard (MDF) mills with 13 production lines using primarily rubberwood.[32] For the production of MDF, rubberwood is usually the sole raw material, whereas chipboard usually uses either rubberwood or material from mixed-species groups.[41]

In 1999, the annual rubberwood production was reported to be 800 000 m^3, with the current stock available at 140 000 m^3. In 1995, rubberwood utilization was estimated at about 2 million m^3, the availability was estimated at about 3.2 million m^3, and the annual volume available up to year 2005 was estimated to be 8–10 million m^3.[34,39] From the recent data shown in Table 7, a decreasing and increasing pattern of the rubberwood saw logs available for further processing emerges; trends are most prevalent in 2004 and 2006 at 1.04 m^3 and 1.38 m^3, respectively. The projected demand for rubberwood sawlogs is estimated to be 1.65 million m^3 for those two years. This means that a shortage of sawlogs was projected, and wooden furniture manufacturers whose staple raw material is rubberwood would be adversely affected. In addition, the data reveal that there was a significant shortfall of rubberwood log supply during the years 2000 to 2006, and this expectation was mostly due to the higher prices

Table 7. Projected industrial demand and availability of rubberwood for primary processing industries in Malaysia from 1995 to 2008[3,25,39,42]

Year	Sawlogs (million m^3)	Sawn timber (million m^3)	Plywood (million m^3)	Projected sawlog requirement (million m^3)
1996	1.13	0.53	0.11	0.76
1998	1.59	0.59	0.16	1.16
2000	1.84	0.62	0.18	1.57
2002	1.43	0.47	0.20	1.60
2004[a]	1.04	0.35	0.18	1.63[a]
2006[a]	1.38	0.45	0.25	1.67[a]
2008	1.89	0.60	0.26	1.70

[a] Projected sawlog requirement will be the mean values of years 2004 and 2006, i.e., 1.65 million m^3

*The data above were projected during year 2002.

paid to the rubber farmers in close proximity to processing centers.[39] However, in 2008, sawlog production increased to 1.89 million m^3. This was because the government started to encourage the private sector to invest in rubber forest plantation under the National Agricultural Policy (NAP, 1992–2010).[42] In addition, the Malaysian Government took steps to provide better incentives through the Pioneer Status (PS) and Investment Tax Allowance (ITA) schemes, introduced through the Promotion of Investment Act (PIA) 1986. Besides, the Rubber Industry Smallholders Development Authority (RISDA) had reorganized the rubber smallholdings within an area to carry out replanting at the same time, so as to benefit from the economies of scale when harvesting and transporting the logs to the mills. Furthermore, RISDA took steps to set up long-term agreements with furniture manufacturers in order to guarantee a continuous flow of rubberwood log supply. Also, the Malaysian government is looking into developing policy to encourage the industry to use larger rubberwood logs for sawn timber conversion only, while the smaller logs or branches (≤10 cm) could be used for the manufacture of medium-density fiberboard (MDF). In this way, there would be less competition for the limited supply of large rubberwood logs and the policy would thus help to ensure that the furniture manufacturers had an adequate supply of raw material.[42]

Expansion of rubberwood effectiveness

Traditionally, rubberwood was a source of fuel, either in the form of firewood for the rural community or for the rubber sheet-curing and brick-making industries. It was also converted into charcoal for use in making steel.[11,43–45] Lew[46] estimated that 67% of the total rubberwood consumed annually was used as fuelwood in Peninsular Malaysia before the development of the rubberwood industry. The processing of rubberwood in Malaysia began in the early 1970s.[9] Rubberwood was then processed into block board cores and converted into chips for pulp and paper making.[31] In the late 1970s, rubberwood was processed into sawn timber for export. As reported by Hong and Sim,[44] the export of rubberwood sawn timber within year 1980–1995 increased more than tenfold in terms of volume and export values because rubberwood was used as a raw material in wood product manufacturing. The sawing process converts logs into sawn timber. In the process, undesirable defects such as knots, pith, and tapping marks are removed. At present, sawn rubberwood timber is widely used in the manufacture of furniture, doors, window frames, moldings, novelty items, and household utility items, whereas rubberwood logs are used to produce veneers, which are usually applied in the manufacture of plywood, hardboard, and solid moldings.[14,31,44,45,47]

The Malaysian rubber industry is renowned internationally for its well-developed and progressive R&D programs that enable the country to establish itself as the world's leader in rubber production, processing, and manufacturing technologies. Recently, the planting of rubber trees solely for wood extraction has been certainly a viable investment for investors when fully integrated with downstream rubberwood processing and product manufacturing. Kadir[48] pointed out that so far, rubberwood is merely considered a residue of the rubber industry and commands a poor price in the open market. The true value of the wood manifests only after it has been processed into semi-finished or final products. The rubber tree has an advantage over many other timber species because it can be exploited for both timber and latex. However, in the case of trees grown only for wood, the returns on investment will obviously improve if the wood is offered at a price competitive to other timber species.[44] With this motivation, several plantation companies, such as Golden Hope Plantations and Guthrie, have moved into downstream processing of MDF to take advantage of the lucrative value-added profits.[48]

According to Anthony,[37] the Malaysian furniture industry in 1998 was still considered to be at an early stage of development. In fact, the successful achievements in the processing and utilization of rubberwood through the R&D efforts of the Forest Research Institute Malaysia have provided the growth impetus for the industry to scale greater heights in the future. On the other hand, the Malaysian furniture industry became an international player because of the technical developments that enabled cheap and plentiful timber to be turned into a value-added product at a competitive price.[26] However, Malaysia's once-cheap raw material is becoming more expensive. This generates several arguments on the trend of increasing rubberwood costs and questions on the long-term sustainability of the whole rubber and rubberwood-based furniture industry. Exports of the furniture industry grew by leaps and bounds from a cottage industry of RM120 million in 1986 to more than RM2.8 billion in 1997. With this, it has been estimated that the export of Malaysian furniture will continue to increase at between 10% and 15% annually to reach an annual export turnover of RM4.1 billion in the future.[37] As an example, curved furniture components, such as chair backs and legs, are commonly made by laminating veneers, which raises the demand of rubberwood veneers and thus prompts the furniture industry to produce its own rubberwood veneers.[9] The main features of this industry that have emerged over the past decade are the remarkable upsurge in production output, the utilization of advanced technology, and the continuous upgrading of the sector. These developments indicate a prospectively vibrant sector of the industry. In 2008, export of furniture shot up to RM8.7 billion, of which 80% was rubberwood-based furniture.[50] On the other hand, the situation on the ground is complicated by several challenges ahead.

Problems concerning rubberwood and its preservative methods

Rubberwood degradation problems

The biodegradation problem is one of the main reasons why rubberwood was less attractive for wood processing industries and was almost neglected in the past, although it was abundant in supply and easily available.[26,32] The high carbohydrate (sugar and starch) reserves deposited in the parenchyma and the absence of phenolic compounds in the wood are the major factors governing the high decay susceptibility of rubberwood.[51] Zaidon et al.[19] stated that these rubberwood products are generally less susceptible to biodeterioration agents than solid wood unless they are used in situations where exposure to moisture or risk of deterioration is likely.

Rubberwood against sapstain and molds

Mold growth on rubberwood is one of major problems in the wood industry.[52] More than 100 000 species of molds exist in the world,[53] such as *Acremonium*, *Aspergillus*, *Cladosporium*, *Fusarium*, *Mucor*, *Penicillium*, *Rhizopus*, *Stachybotrys*, and *Trichoderma*.[54] Molds require nutrients such as sugar, starch, and protein; suitable temperatures (ideally between 21° and 29°C); oxygen; and moisture to survive.[55] Rubberwood tends to be infested with molds that cause the wood color to change from pale yellow to dark green or even black.[31] Growing incipient molds can normally be removed from the surface by brushing or surface planning.[53,56]

Among the wide variety of fungi, microfungi belonging to the Fungi Imperfecti can also cause rubberwood decay, either in freshly felled logs or in freshly sawn timber form.[8] *Aspergillus nige*r is one of major fungi identified from rubberwood surfaces; *Aspergillu*s is a cosmopolitan fungus with air-borne infective propagules and it routinely contaminates food, feed, and agricultural commodities such as wood. Also, it has been reported that *Aspergillus nige*r is a serious problem from the viewpoint of public health.[52]

The causal sapstain fungus *Botryodiplodia theobromae* is identified through the resultant bluish discoloration that develops on rubberwood and other light-colored hardwood logs and freshly sawn timber (Fig. 1). This fungus penetrates the ends of the logs within 1 week after felling, and the infection is found to be particularly severe during the rainy season.[8] Based on the literature, the optimum temperature is 30°C for the initial establishment and growth of *B. theobromae*. No growth is found at 50° and 60°C. However, the fungus can tolerate and survive at high temperatures once it is established inside the wood.[2] Therefore, Hong et al.[8] recommended kiln drying at a temperature of 65°C for at least 3 h to kill the fungus. The mycelium of the fungus is thick and brown and is usually present in the parenchymatous tissues of the sapwood, which is rich in starch and other

Fig. 1. Sapstain (or blue stain) on rubberwood[51]

Fig. 2. Dipping of freshly sawn rubberwood in preservative mixture[21]

Fig. 3. Vacuum-pressure process for treatment of sawn rubberwood[21]

Table 8. Percentage weight loss of rubberwood test blocks by a range of wood-decay fungi over 10 weeks[51]

Class	Fungus	Weight loss (%)
High weight loss (>50%)	*Antrodia* sp.	53.8
Medium weight loss (25%–50%)	*Nigroporus vinosus*	39.0
	Lentinus sajor-caju	35.2
	Phellinus sublinteus	27.6
	Gloeophyllum striatum	25.4
Low weight loss (0.1%–25%)	*Polyporus grammocephalus*	24.1
	Lenzites acuta	22.3
	Microporus affinis	19.2
	Trametes modesta	18.8
	Lentinus squarrosulus	18.6
	Coriolopsis aspera	17.6
	Ganoderma austral	16.7
	Lentinus polychrous	16.5
	Flavodon flavus	16.0
	Trametes socotrana	15.3
	Microporus xanthopus	14.2
	Trametes feei	13.8
	Pleurotus djamor	13.5
	Pycnoporus sanguineus	13.0
	Trametes menziesii	11.2
	Schizophyllum commune	10.4
	Trametes sp.	10.1
	Rigidoporus microporus	9.5
	Ganoderma applanatum	9.5
	Pleurotus djamor	8.7
	Lentinus strigosus	8.2
	Gyrodontium versicolor	7.9
	Lenzites (Trametes) elegans	7.8
	Trametes carneo-nigra	7.8
	Trametes cotonea	7.6
	Earliella (Trametes) scabrosa	6.9
	Phellinus setulosus	5.9
	Stereum ostrea	5.9
	Microporellus inusitatus	4.1
	Penillus sp.	4.1
	Tinctoporellus epimiltinus	3.5

nutrients. The mycelium may be found in both fiber and vessel lumina, albeit less frequently, using these wood cells as pathways to reach new parenchymatous tissues. The fungus uses these wood cells as pathways to reach new parenchymatous tissues. The hypha has a unique ability to constrict when passing from one fiber lumen to another through pits in the wood cell walls.[8]

Structural components and wood strength are not significantly degraded by *B. theobromae*, however.[8,51] In addition, staining microfungi from rubberwood in India, such as *Fusarium decemcellulare*, *Aspergillus sydowii*, and *Penicillium citrinum*, are among the main surface colonizers. They simply thrive on the readily available carbohydrates occurring in abundance in the parenchyma cells of the rubberwood but do not act to break down the lignocellulosic components of the wood.[56]

Rubberwood against wood-decaying fungi

Wood-decaying fungi that cause severe breakdown of wood are characterized either as brown rot and white rot (generally caused by Basidiomycetes) fungi or as soft rot (caused by Ascomycetes and Fungi Imperfecti) fungi.[8] Wong[7] showed that the susceptibility of rubberwood to the three major types of wood rot fungi is of the following order of severity: substrate mass loss due to soft rot (*Chaetomium globosum*) > white rot (*Pycnoporus sanguineus*) > brown rot (*Tyromyces palustris*). Salmiah[51] stated that the capacity of both white rot and brown rot fungi to decompose rubberwood is much reduced compared with the effect on temperate timbers (e.g., sweetgum and southern yellow pine). This may be because many tropical woods contain a higher proportion of tannins and phenolic compounds that have better fungistatic effects compared with temperate woods. As such, rubberwood appears to be most susceptible to soft rot decay compared with other nondurables such as punggai (*Coelostegia griffithii*), jelutong (*Dyera costulata*), and kayu arang (*Diospyros* spp.). However, against the white rot fungus *Coriolus versicolor*, rubberwood has been found to be more susceptible than nondurable jelutong and ramin (*G. bancanus*).[8]

Polyporaceae fungi are associated with major tree losses in rubber plantations in the equatorial and humid tropics. Generally, they cause white or brown root rots in the stand-

Table 9. Chemical preservation of wood from deterioration[58]

Method	Description	Advantages	Disadvantages
Creosote and creosote solutions	Creosote, an oily by-product of making coke from bituminous coal, is widely used as a preservative for products such as railroad ties, large timbers, fence posts, poles, and pilings	Toxic to wood-destroying fungi, insects, and some marine borers Low volatility Insolubility in water Ease of handling	Dark color, strong odor Oily, unpaintable surface Tendency to bleed or exude from the wood surface Toxic fumes
Oil-based preservatives	Insoluble in water. Usually dissolved in petroleum or other organic solvents in order to penetrate wood. Research developments have recently made available oil-based preservatives formulated as water- in-oil emulsions or dispersions in water	Toxic to fungi, insects, and mold Can be dissolved in oils having a wide range of viscosities, vapor pressures, and colors Low solubility Can be glued, depending on the diluents or carrier Ease of handling and use	Oily, unpaintable surface For some applications, provides less physical protection to wood than creosote Should not be used in homes or other living areas because of toxic fumes Toxic and irritating to plants, animals, and humans
Water-based preservatives	Includes various metallic salts and other compounds. The principal compounds used are combinations of copper, chromium, arsenic, and fluoride. Used widely for poles, pilings, and timbers	Treatment presents no hazard from fire or explosion The wood surface is left clean, paintable, and free of objectionable odors Safe for interior use and treatment of playground equipment Leach resistant	Unless redried after treatment, the wood is subject to warping and checking Does not protect the wood from excessive weathering

ing tree, which subsequently affect the living stem.[57] The other species of Basidiomycetes isolated from rubberwood in association with root disease are *Trametes corrugata* (white rot), *Schizophyllum commune* (white rot), *Lentinus blepharodes*, *L. palisotii* (white rot), *G. applanatum* (white rot), *Fomes senex* (white rot), *Polyporus zonalis* (white rot), and *Poria* sp.[58] It has been noticed that in Malaysian plantations, *S. commune* grows readily on rubberwood logs. This fungus is edible, grows on rubberwood after a few weeks of felling, and is therefore frequently collected by local people for food consumption. *L. palisotii* and *G. applanatum* are the most destructive to rubberwood among these local isolates, while *F. senex*, *S. commune*, and *Poria* sp. are poor degraders.[8] Furthermore, *L. palisotii* has been reported as a more active wood degrader than *G. applanatum*.[56]

An experiment was carried out by Salmiah[51] based on the percentage weight loss of rubberwood test blocks using a range of wood-decaying fungi over 10 weeks (Table 8). It was found that *Antrodia* sp. was the most destructive fungi, causing a weight loss of 53.8%, followed by *Nigroporus vinosus*, *Lentinus sajor-caju*, *Phellinus sublinteus*, and *Gloeophyllum striatum* with weight losses between 25.4% and 39.0%. On the other hand, rubberwood was considered very durable against *Microporellus inusitatus*, *Phellinus* sp., and *Tinctoporellus epimiltinus*, as low weight losses were recorded.

Rubberwood preservation method

Generally, four criteria are applied to judge the sustainable development of wood preservative methods[59]: (i) the preservative must be safe to handle and apply, (ii) the preservative must be effective against the target wood-biodeteriorating organism, (iii) the preservative must be stable and provide the required prolonged effectiveness in treated wood, and (iv) the preservative must be cost effective. Table 9 shows three classes of wood preservatives using chemicals: creosote and creosote solutions, oil-based preservatives, and water-based preservatives.[60]

There are several processes involved in treating rubberwood, either in the form of logs or sawn timber, such as dip treatment (Fig. 2), dip-diffusion, pressure treatment, vacuum-pressure (Fig. 3), the oscillating pressure method (OPM), and the double-vacuum process. For temporary protection from staining of cut ends of logs, 3% sodium pentachlorophenoxide or 2% captafol in a bituminous compound may be applied. Freshly felled logs can be kept under water in log ponds to protect them against splitting and attacks by insects and fungi.[21] For sawn timbers, it is necessary to treat them immediately after sawing to prevent the penetration of staining fungus. As an example, sawn rubberwood can be protected before kiln seasoning through the dipping process for a few seconds in a solution of 0.5%–1% sodium pentachlorophenate and 2% borax in water. Pressure impregnation for total protection gives satisfactory results for rubberwood due to its permeability.[16,21]

An economical schedule for the industrial-scale treatment of rubberwood using boron compounds in the form of disodium octaborate tetrahydrate ($Na_2B_8O_{13}\cdot 4H_2O$), disodium tetraborate decahydrate ($Na_2B_4O_7\cdot 10H_2O$), and boric acid (H_3BO_3) has been developed, particularly for indoor applications, to protect from insects borers and fungi.[21,33] Boric acid serves as an effective fungicide, insecticide, and flame retardant.[61] Boron compounds are also odorless and relatively less toxic compared with other preservatives (e.g., lindane), which can pose a serious health

Table 10. Weight loss in test blocks of rubberwood over 4 weeks[62]

Fungus	Mean weight loss (%) Treatment BB	Mean weight loss (%) Treatment BB + NaPCP	Weeks taken to attain 60% weight loss in reference blocks
Ganoderma applanatum	1.24^{a}	2.25^{a}	23
Lenzites palisotii	2.87^{a}	1.60^{a}	13

[a] Figures superscribed by the same letter are not significantly different at $P = 0.50$ level

BB, boric acid–borax; NaPCP, sodium pentachlorophenoxide

Table 11. Effective dose at 50% inhibition (ED_{50}) ($\mu g ml^{-1}$) for pyrolytic oil on different fungi[65]

Pyrolytic oils	Effective dose at 50% inhibition (ED_{50}) ($\mu g ml^{-1}$): *Coriolus versicolor* (White rot fungus)	*Gloeophyllum trabeum* (Brown rot fungus)	*Botryodiplodia theobromae* (Blue stain fungus)
A	736.88	640.77	661.30
B	1107.39	1944.46	1237.94
C	1731.41	5619.53	1587.45

A, 200°–235°C; distilled from tar collected at pyrolysis run with intrinsic temperature of 700°C

B, 170°–200°C; distilled from tar collected at pyrolysis run with intrinsic temperature of 700°C

C, 200°–235°C; distilled from tar collected at pyrolysis run with intrinsic temperature of 500°C

hazard to workers performing the treatment and the processing of treated timber.[21] Salamah et al.[62] reported that boron treatment through the dip-diffusion and full-cell processes are two common methods for the preservation of rubberwood. Hence, experiments were carried out on rubberwood treated with preservatives, namely boric acid-borax (BB) and BB + sodium pentachlorophenoxide (NaPCP), by a diffusion process.[63] As can be seen in Table 10, the average weight loss of treated wood was much less than 10%, which indicated that the rubberwood became highly resistant against the two white rot fungi *Ganoderma applanatum* and *Lenzites palisotii* after the treatment. In addition, Gnanaharan (1984)[63] also evaluated the effectiveness of BB, BB + NaPCP, and BB + Akzo ES 255, an alkyl ammonium compound, against mold and sapstain fungi during diffusion storage and found that BB + NaPCP was the most effective combination against mold (92%) and sapstain (98%). BB alone gave only 2% control against mold and 97% against sapstain. Furthermore, Salamah and Mohd Dahlan[64] carried out an experiment on rubberwood by applying vacuum-pressure treatment using boron-based preservatives. They showed that treatment parameters of 1 h at pressure using 2% boron solution were only sufficient to treat 25-mm-thick rubberwood timber to achieve 0.2% boric acid equivalent in the core area.

Dhamodaran and Gnanaharan[65] suggested that rubberwood that possesses medium-strength properties should be treated with a fixative-type preservative for use in construction. Highly toxic, but safe once fixed, CCA preservatives are widely used in many countries due to their efficacy and cost-effectiveness. Rubberwood can be easily treated by the Bethell vacuum-pressure process using CCA preservative. Recently, Akhter[2] studied the feasibility of the preservative treatment of rubber timber using soaking and the pressure process to ensure that the timber is not degraded before or during service. It was found that rubberwood could be treated by the soaking process using mild conditions, with the moisture content near the fiber saturation point. In fact, low-cost water-based preservatives borax–boric acid and copper–chrome–boron also gave adequate protection to rubberwood. However, Mohd Dahlan et al.[21] reported that CCA-treated rubberwood is rarely used in making furniture because of the unnatural color of the treated wood, but it can be used for construction or structural purposes to ensure resistance against termites and other biodeteriorating organisms. Zaidon et al.[19] also reported that the incorporation of boron compounds or CCA in urea formaldehyde and melamine formaldehyde-bonded particleboard enhances the resistance of the boards against white rot fungus.

On the other hand, synthetic pyrethroid-formulated preservatives, such as cypermethrin, deltamethrin, and permethrin, have also been investigated for their efficacy in protecting rubberwood from fungi and termites. Zaidon et al.[22] proved that the resistance of particle boards to white rot fungus or termites could be enhanced through the incorporation of a small amount of pyrethroid-formulated preservatives by spraying during blending of furnish. However, the cost is the only drawback of using synthetic pyrethroid in preserving rubberwood, as its price is much higher than some of the commonly used formulations.[21]

The heavy oils of wood tars are generally used as preservatives, disinfectants, and stains; creosote or oil prepared from coal tar distillation has long been used as wood preservative.[66] Inoue et al.[67] showed that sapwood stakes of *Cryptomeria japonica* and *Fagus crenata* treated with creosote oil (with or without heavy oil) or with coal tar were generally sound after 28 years. Table 11 gives the ED_{50} values obtained from probit-log concentration analysis for each fungus with the corresponding oil sample tested. It is known that antifungal activity may not only be due to the individual constituents but often to the total oil composition.

Based on the work of Diawanich et al.,[68] an attempt to reduce drying time and energy by accelerating the drying rate might easily result in various defects within the kiln-dried lumber, e.g., warps, internal splitting, surface checking, and end checking. Malik[61] introduced a rubberwood treatment method that involves rapid kiln drying of wet, sawn timber to low moisture contents under vacuum. At the end of the drying cycle, a volatile borate ester is injected into the cylinder. Under reduced pressure, the ester vaporizes and penetrates the wood material, where it reacts with water in the wood to form the active ingredient boric acid. The elimination of solvent allows the treated timber to remain dry, and thus ready for immediate use upon removal from the treatment vessel. The total process from green, sawn timber to dry treated wood using this method took approximately 30 h, compared with conventional kiln drying and CCA treatment that took approximately 7–16 days, depending on the thickness of the timber.[69] The other advantages of this new gas-phase process include reduction in handling, improved timber quality, reduced capital costs (only a single drying and treatment plant is required), safer wood treatment processing, and environment-friendly wood preservation. This preservation method has been granted patents in the United Kingdom and New Zealand and is currently being adopted in South Africa.[61]

In Malaysia, the double-vacuum process was introduced for the treatment of seasoned rubberwood and semi-finished products using light organic solvent-based preservatives (e.g., low-viscosity agents containing synthetic pyrethroids or organotin compounds, among others) particularly to prevent borer infestations. This process is appropriate for the treatment of semi-finished furniture compounds or moldings of rubberwood, as the organic solvent will not cause swelling or shrinkage after treatment compared with the aqueous formulations used for the treatment of freshly sawn timber.[21]

In addition to the processes described above, OPM is a variation of the vacuum-pressure process and is appropriate for treating rubberwood with high moisture content using nondiffusible preservatives or for treatment of refractory timbers. This method is widely used in Germany and Switzerland, particularly for treating poles of spruce or white fir, and in New Zealand for treating radiata pine using boron preservatives. However, in Malaysia, this treatment method is applied to rubberwood using either preservative-containing boron compounds or synthetic pyrethroids.[21,62] However, the efficiency in terms of penetration and retention of compounds has not been assessed.

Currently, chemical fungicides (e.g., methyl bromide) are commonly used to control the growth of mold.[52] As reported by Zhou et al.,[12] commercial fungicides for agricultural uses, such as chlorothalonil, copper oxine, methylene bis thiocyanate, carbendazim, benomyl, isothiazolinone, and propiconazole, can also be used for the temporary protection of rubberwood. However, sodium pentachlorophenol is not recommended due to its high toxicity and the fact that it also contributes to the severe corrosion of the drying kiln components and thus turns the wood brown.

Over the past few years, an increasing demand for toxin-free lumber in such applications as food packaging, kitchenware, children's toys, and indoor wooden structures, has been a driving force in the development of less toxic approaches to wood protection. Based on the studies made by Matan et al.,[52] essential oils can be utilized as alternative choices to chemical fungicides; essential oils have been widely used in food applications and their antifungal effects have been extensively studied. As an example, Matan et al.[70] investigated the antifungal activities of essential oils (e.g., peppermint oil and eucalyptus oil) and their main components (e.g., methanol and eucalyptol, respectively) against molds such as *Aspergillus niger*, *Penicillium chrysogenum*, and *Penicillium* spp. as well as against the white rot fungus *Trametes versicolor*, which can be easily identified from rubberwood surfaces. The results showed that both provided only moderate resistance to fungal decay but high resistance to termite attack. In addition, a previous study by Matan and Matan[71] showed that cinnamon oil and clove oil, natural preservative substances that are not harmful, can be used to inhibit the growth of molds, yeasts, and bacteria. Soliman and Badeaa[72] found that cinnamon oil (≤500 ppm) could inhibit *Aspergillus flavus*, *A. parasiticus*, *A. ochraceus*, and *Fusarium moniliforme* on potato dextrose agar medium.

Future alternative of biological-based control agents

Biocontrol agents are promising alternatives to chemical control of molds.[73] As reported by Verma et al.,[74] fungi-based biological control agents have gained wide acceptance due to their broader spectrum in terms of disease control and production yield. Biofungicides are usually produced from secondary metabolites of fungi under an active culture cultivation process in which the fungi are not essential for vegetative growth in pure culture.[75] *Trichoderma* biofungicides have been modest biological control agents over the past 20 years.[74,76] For example, *Trichoderma harzianum* ATCC20746 has been developed for the treatment of strawberries against gray mold *Botrytis cinerea*.[76] There are also various fungal species that can be utilized as biological control agents, which may provide effective activity against various pathogenic microorganisms, such as *Ampelomyces quisqualis*, *A. niger*, *Candida oleophila*, *Chaetomium cupreum*, *C. globosum*, *Coniothyrium minitans*, *Cryptococcus albidus*, *Gliocladium virens*, *Gliocladium catenulatum*, *Fusarium oxysporum*, *Phlebiosis gigantea*, *Pythium oligandrum*, *Rhodotorula glutinis*, *T. harzianum*, and *Trichoderma polysporum*.[75–79] Based on the above observations, the biological control concept can be applied to the rubberwood industry for mold inhibition; however, at present, there are no reports on the usage of biofungicides for rubberwood treatment.

Conclusions

Rubberwood (*Hevea brasiliensis*) has been recognized as an environmentally friendly wood material for a number of years. Attention was originally focused on forest-based industries, especially the wood-based panels sector, which produces products such as particle/chipboard, cement-bonded board, and medium-density fiberboard (MDF). Due to its abundant availability and unique properties, rubberwood has provided us with the competitive edge against other established furniture producers. Rubberwood itself is uniform in its pale cream color, wood texture, and density, and these meet the basic requirements of furniture production. Its light color allows it to be stained or finished in solid color. However, mold, sapstain, and wood-decaying fungi are observed on the wood. In view of the high severity of the decay problem, there is a need for a quick preservative treatment of rubberwood to prevent infestation by biodeteriorating organisms in warm and humid tropical countries such as Malaysia. Although chemical fungicides and chemicals such as boron compounds are commonly impregnated into rubberwood, biological alternatives that are environmentally friendly and have low mammalian toxicity are needed in order to extend the rubberwood market to other applications such as food-related materials and children's toys, areas in which health is of the greatest concern.

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