Development of experimental kiln-drying schedules for different types of coconut (*Cocos nucifera* L.) palm wood flooring

by

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DECLARATION

I, hereby declare that this thesis entitled **"DEVELOPMENT OF EXPERIMENTAL KILN-DRYING SCHEDULES FOR DIFFERENT TYPES OF COCONUT (*Cocos nucifera* L.) PALM WOOD FLOORING"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Place: Vellanikkara

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Certified that this thesis entitled **"DEVELOPMENT OF EXPERIMENTAL KILN-DRYING SCHEDULES FOR DIFFERENT TYPES OF COCONUT (*Cocos nucifera* L.) PALM WOOD FLOORING"** is a record of research work done independently by Mr. Shibu. C under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

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We, the undersigned members of the advisory committee of **Mr. Shibu. C**, a candidate for the degree of **Master of Science** in Forestry with major in forest products and utilization, agree that the thesis entitled **"DEVELOPMENT OF EXPERIMENTAL KILN-DRYING SCHEDULES FOR DIFFERENT TYPES OF COCONUT (*Cocos nucifera* L.) PALM WOOD FLOORING"** may be submitted by Mr. Shibu.C, in partial fulfilment of the requirement for the degree.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

1. INTRODUCTION

Global wood consumption has increased by more than 1% per annum in recent years, but it will rise by more than 3% per annum over the next 30 years. This expected rise in wood consumption is set against a constrained supply of wood globally (GH, 2020). In India, the import quantity of industrial round-wood increased to 4.4 million m^3 in the year of 2019. In the last year (2020), it dramatically decreased to 2.6 million m^3 (FAOSTAT, 2021) due to the Covid-19 pandemic situation (ITTO, 2020).

The production of wood raw materials has declined because of urbanization and decrease in productivity. Apart from that, most of the valuable species for timber, like Eucalyptus and Acacias pose serious ecological and social concerns. This in turn implies for the future an insufficient raw material base for the timber industry. People across the world are concerned about the ecologically and socially, which might lead to a drive for readily renewable lesser known species - “it is a species that is not being to put best advantage” (Yeom, 1984) like coconut palm wood. The concept of replacing forest hardwood tree cutting with items made from coconut palm wood is to meet the demand for wood as well as being ecologically conscious.

India has a long coastline of 7,517 km and also third in the world in terms of total area planted with coconut palms (2.14 million hectares), accounting for about 20% of the total planted area. However, many of them are unproductive palm (CDB, 2015) and required extensive replanting. Conversion of coconut plantations to residential areas were intended to supplement the low-cost supply of raw materials for the wood industry with equally durable construction materials for the state's homes, as well as for export and saleable wood products.

The optimal use of any wood must be based on both its fundamental and processing characteristics. The most significant processing features are the drying properties which ensure the effective utilization and high-quality wood products (Effah and Kofi, 2014; Hoadley, 2000). The forte of viable seasoning lies in keeping a balance between the evaporation of water from the surface of the wood and the movement of water from the inside of the wood to the surface (Desch and Dinwoodie, 1981). The initial moisture content of coconut palm wood varies from 60% in high density wood to 230% in low density wood (Kollmann, 1983). Much focus is placed on manufacturing seasoned wood as fast and cost-effectively within stipulated quality limitations.

Effective utilization of lesser-known wood has gained much prominence in the current scenario. Coconut palm wood is now popular and follows the success achieved in the utilization and commercialization of teak and other hard-woods. This is because coconut palm wood is one of the most suitable, versatile, and aesthetic-pleasing materials not only for building but also for flooring and paneling. The drying and basic properties of coconut palm wood are the basis for the development of flooring and its utilization. Therefore, studies on the drying characteristics, basic properties, and development of the drying schedule are of great significance.

The following study aims to develop an experimental kiln drying schedule through the analyses of the green moisture content, basic density, drying rate, and defects based on a quick drying test for different coconut palm wood flooring (solid flooring, parquetry, and engineered overlay).

2. REVIEW OF LITERATURE

Overview

This section includes a review of literature under the following sub-topics: background, global distribution of coconut palm trees, anatomical properties, physical properties include moisture content, density, and shrinkage, wood drying, fiber saturation point (FSP), equilibrium moisture content (EMC), drying defects, fundamental principles of kiln drying, drying schedule, and coconut palm wood flooring.

2.1 Background

Cocos nucifera L. is known as "the tree of life" because each and every part of the coconut tree is utilized to make useful things for the community. The average range of height (15m-20m) or two by third of stem height is widely used for structural application. All types of density (low, medium, and high) are suitable for furniture and interior decorating (Killmann and Fink, 1996). While only the denser portion of coconut wood is used for structural loads or bearing components (Killmann, 2001). From an economic perspective, the use of coconut wood and its marketing can provide significant assurance in the present and future, as the price of coconut is half that of ordinary wood, the supply of desirable tropical timber is significantly reduced (Arancon, 2009), and many projects have been launched to protect the coconut industries of the countries that are the cornerstones of the rural economy (Anoop *et al.*, 2011). Large stands of unproductive coconut trees would have to be felled and replaced with high yield varieties and these replanting programs would undoubtedly unleash massive amounts of raw materials for use. Finally, new technologies and corresponding infrastructures were developed to ensure successful production using coconut palm wood. It is more feasible to optimal use resources rather than allowing them to go to waste. From the standpoints of economics, environment, and forest conservation, interest in coconut plantations will generate income and employment; moreover, reduce the pressure on natural forests by providing alternative raw materials.

2.2 Global distribution of coconut palm trees

The coconut palm is found all over the world. Common seen between 23 degrees north and south of the equator in both tropical and subtropical areas. The distribution comprises more than 93 countries across Asia, Africa, America, and Oceania (Chan and Elevitch, 2006), which covers an area of 12.1 million hectares and 371.3 million senile coconut trees in plantations (Keanu, 2020). In the Asia-Pacific region, approximately 45% of the coconut palms in the world are located (Arancon, 2009) and 75% of the total area (9 million hectares) under the coconut crop is contributed by 3 countries, namely, India, Indonesia, and Philippines (Chowdappa and Jayasekhar, 2017).

In India, the coconut palm tree is found in the hot, humid regions of Andhra Pradesh, Bangladesh, Karnataka, Gujarat, Maharashtra, Tamil Nadu, Kerala, and Orissa and is native to Cocos Islands and the North Andaman Islands (Swathi *et al.*, 2021).

2.3 Anatomical properties of Coconut palm wood

The coconut tree has a long stem that can attain heights up to 30 m and a diameter of 30 cm. Coconut trees are monocotyledons and so instead of bark, stems have an outer epidermis layer, which is usually 1–2 cm thick that hardens into a protective layer (Tomlinson, 1961). Because there is no external development or secondary growth due to the absence of a cambium layer (Fathi, 2014). As compared to woody dicots, coconut palms have very distinct anatomical features, such as there is no secondary development, vascular cambium, annual rings, heartwood, ray cells, branch, knots, discernible rise in diameter with age, and difficulty to separate the bark from wood because it's not clearly marked (Butterfield and Meylan, 1997).

Coconut stem wood, based on the density of the vascular bundles visible to an expert eye, has three zones; the core zone, the sub-dermal zone, and the dermal zone. The dermal region consists of nearly 70 vascular bundles per cm^2, The sub-dermal region has just above 40 vascular bundles per cm^2, and the central core zone has approximately fewer than 20 vascular bundles per cm^2 (Keanu, 2020).

The vascular bundles and relative quantity of fibers within the bundles are denser in the trunk periphery. It occurs as red-brown dots sprinkled in a yellowish parenchymatous ground tissue in a cross-section. Coconut stem is made up of vertically bound vascular fiber bundles that are composed of honeycomb-like prismatic cells and thick fibers, while low-density parenchyma ground tissue is primarily composed of thin-walled polyhedral parenchyma (Gonzalez and Nguyen, 2016). It serves as a holding function or storage function of starch and specialized tannin cells that include polyphenols and raphide sacs, as well as pectin fibers. Each vascular bundle is arranged in a multi-helix formation and made up of xylem, phloem, axial parenchyma, and sclerenchyma thick-walled fibers (Gibson, 2012).

2.4 Physical properties of Coconut palm wood

The word "wood" for coconut stems is dubious because monocotyledons produce solid stems but not true wood, which have very different properties (Djokoto, 2013). Coconut palm wood comprises red-brown dot vascular fiber bundles spread non-homogeneously on yellowish ground parenchymatous tissues. This vascular fiber bundle consists of nutrient and water transport systems of phloem and xylem vessels respectively, besides well thick-walled fibers around the transport system provide strength and density. Similarly, the low-density ground parenchyma serves as a storage area of starch and other substances (Killmann and Fink, 1996).

The physical properties of coconut palm wood over cross-section and height vary dramatically, because of the non-homogenous distribution of anatomical features. The physical characteristics, like moisture content, density, and shrinkage of coconut palm wood depend on the distribution of bundles, proportion and thickness of fibers and ground parenchymatous cell walls (Butterfield and Meylan, 1997).

2.4.1 Moisture content of Coconut palm wood

The moisture content of coconut palm wood is expressed as a percentage (%) and varies from 50% at the bottom dermal portion to 400% at the top core portion of the stem **(**Killmann, 1983**)**. According to Richolson and Swarup (1977), moisture content increases with stem height significantly from the peripheral region to the middle of the coconut palm wood. This trend of water distribution is strongly associated with the fraction of parenchymatous ground tissue that has more water holding capacity. In other words, the higher density implies a larger number of vascular bundles, resulting in less water storage capacity or less moisture content. The tropical environment conditions and highest moisture content of coconut palm wood provide a favourable habitat for fungal growth, and consequently, felled coconut logs need to be processed rapidly to reduce the effect of fungal attack (McGavin *et al.*, 2019).

Kloot (1952) discovered a close association of moisture content with basic specific gravity of coconut wood and Similarly, Arancon (1997) also discovered a relationship with basic density. They concluded that moisture content is negatively associated with basic density, which means, moisture content increases as density decreases and vice versa. Desch (1996), Matan and Kyokong (2003), and Kord *et al.* (2010), found that higher shrinkage, higher Modulus of Elasticity (MOE), and higher Modulus of Rupture (MOR) are associated with higher wood density.

2.4.2 Density of Coconut palm wood

Coconut palm wood's basic density, or oven-dry to green volume, falls with height and, at any given height, decreases from bark to core. Besides, the basic density of coconut palm wood increases with age at any a given height. The basic density of old coconut palms wood varies from 0.105 g/cm^3 near the crown to 0. 875 g/cm^3 near the bottom dermal portion (Ohler, 1999).

Killman (1983) calculates the oven-dry density range (0.11 g/cm^3-0.85 g/cm^3) of coconut palm wood from the top to the lower periphery. According to Rana *et al.* (2015), the average oven-dry and air-dry density of coconut stem was 0.46g/cm^3 and 0.40 g/cm^3, respectively. There was a significant variation in oven-dry and air-dry density at top and middle of the coconut stem, but not between core and peripheral sections.

The heterogeneity of physical and mechanical properties of coconut palm wood influences processing methods and end products. The coconut palm wood has been classified into three groups based on basic density or oven-dry density (Killmann and Fink, 1996 and Siddiqui, 1997) as follows:

I. Dermal wood (high-density wood) with a density greater than 0.6 g/cm^3 has superior strength properties to some conventional woods. As a result, high-density coconut palm wood can be used for load-bearing structural elements such as floor tiles (parquet) and floor joists, as well as outdoor flooring after proper treatment.
II. Sub-dermal wood (medium-density wood) ranging from 0.40g/cm^3 to 0.59g/cm^3, which can be used for overly flooring, walling, door and window frames.

III. Core wood (low-density wood) less than 0.40g/cm³, used for non-load structures (e.g. the panels and the walls (Indoor use only)).

2.4.3 Shrinkage of Coconut palm wood

Arancon (1997) quoted in his studies that "Shrinkage or swelling which accompanies a decrease or increase in moisture content below the fiber saturation point. The shrinkage and swelling cause drying defects such as checks and splits. Unlike conventional wood, where tangential shrinkage is almost twice the radial shrinkage, the tangential and radial shrinkage of coconut palm wood is not significantly different". At various height positions, the radial, longitudinal, tangential, and volumetric shrinkage of coconut palm wood varied. Rana *et al.* (2015) found that there was no statistically significant difference in tangential, radial, longitudinal, and volumetric shrinkage at various height positions. The shrinkage between the peripheral and core part was also non-significant. His finding shows that there was no correlation between height and shrinkage value, and he calculated average shrinkage value at radial (5.1-5.4%), tangential (5.3-5.8%), longitudinal (0.9-1.2%) direction and volumetric shrinkage (11.8%).

The calculation and pattern of shrinkage intensity in coconut wood was contradictory. For example, Richolson and Swarup (1997) reported volumetric shrinkage of coconut palm wood was 10% for the outside section and 5% to 7% for other sections (increasing from core to periphery). Like Richolson and Swarup (1997), McConchie (1975) cited by Fathi (2014) reported that 10% for the outside section but more than 21% for low-density coconut wood, and he states that shrinkage decreases from core to periphery. According to Richolson and Swarup (1997), shrinkage and swelling values are correlated to oven-dry density and increase from the core to the periphery of coconut palm wood. In the case of height, it also increases gradually up to 10 m, then decreases. Because vascular bundles dominate, the density and shrinkage are directly linked to the number of vascular bundles per unit area (Killmann, 1983).

2.5 Wood drying

Wood drying is a crucial stage in the preparation of products that require the wood to be in a stable state before usage or drying wood to a moisture content range suitable for the conditions and uses (McGavin *et al.*, 2019). In general, the drying rate of wood is influenced by anatomical characters like vessels, fibre walls, parenchyma, ray cells and their structure. The larger diameter of wood vessels is easier to dry, although the presence of tyloses, silica crystal, and wood ray cells are wood drying inhibitors.

Wet weather and low temperatures are preferable than hot and dry conditions for retaining log quality. A sprinkler system may be used if logs are to be stored for an extended period in warm or hot weather. This sprinkler system will help to prevent drying defects such as end-splitting and end-checking of logs, as well as taint, fungal, insect, and rot deterioration (McGavin *et al.*, 2019). These organisms cannot grow in woods with a moisture level of less than 20% (Wengert, 2006). Dry timber is lighter in weight, saving transportation and handling costs, stronger in most load-bearing structures, and better for woodwork, equipment, finishing, and glue than greenwood. Moreover, on dry wood, paints and finishes endure longer. Drying improves the electrical and thermal insulating qualities of wood (Walker, 2006). However, according to the study of Sehlstedt-Persson and Wamming (2010), the drying process may have negative effects on the natural durability of wood.

2.6 Fiber Saturation Point (FSP)

The Fiber Saturation Point (FSP) of wood is described as the moisture content (%) of wood reached when all the fibers are saturated with colloidal water, but no free water exists in the capillary structure (Kollmann and Cote, 1968). The moisture condition above the fiber saturation point is required for decay by fungi where free water is available for the transport of minerals, enzymes, and oxygen (Walker, 2006). Below this fiber saturation point, infected wood will generally not decay because the fungus cannot grow and also the mechanical properties of wood increase with decreasing moisture content from the fibre saturation point because of water loss from the cell wall, but shrinkage begins when drying proceeds (Skaar, 2012).

Walker (2016) has pointed out that fiber saturation point value depends on the chemical and structural composition of wood. The fibre saturation point of ring-porous and semi-ring-porous broadleaved woods is low (23%) compared to the fibre saturation (33%) point of diffuse-porous broadleaved woods, as well as coniferous woods with a high resin concentration have a fibre saturation point of 23%, whereas those with a moderate resin content have a fibre saturation point of 27%. The fiber saturation point for various woods varies significantly, ranging from 20% to 35% moisture content, with a few exceptions below or beyond these amounts (Kollmann and Cote, 1968).

2.7 Equilibrium Moisture Content (EMC)

The moisture content level of wood at which the wood does not absorb or lose moisture because it is in equilibrium with the surrounding ambient atmosphere. This moisture content level is designated as the equilibrium moisture content (Kollmann and Cote, 1968) which depends upon the wood material as well as the temperature and relative humidity of the atmosphere (Redman and McGavin, 2008). According to Saiu (1995), the equilibrium moisture content is “The amount of moisture that remains in the wood at this stage is in equilibrium with water vapour pressure in the ambient space and varies very slightly with species, mechanical stress, drying history of wood, density, extractive content, and the direction of sorption in which the moisture change takes place (i.e. adsorption or desorption).”

2.8 Wood drying defects

Drying defects are any irregularities in wood or blemishes, which may develop and reduce the utility value of wood when it's subjected to high-temperature conditions (Chen *et al.*, 1997). According to Arancon (1997), swelling and shrinkage of coconut wood can create defects such as splits and checks. The inner zone of coconut wood is extremely prone to drying defects when compared with the outer portion of the wood. Drying of wood below the Fiber Saturation Point (FSP) is a pure diffusion process but complicated. Stamm (1964) observed simultaneous diffusion of water vapour through the void structure and bound water diffusion through the cell walls of wood in *Picea sitchensis*.

The moisture content of wood occurs in three forms: Hygroscopic or bound water in the cell walls; free or liquid water in the cell cavities; and water vapour in the cell cavities. This free water and water vapour in the cell cavity escape completely from the wood, then bond water during the normal drying process. The main cause of wood drying defects is drying stresses and depends on two major factors: Hydrostatic tension or volumetric stress, and differential shrinkage. On the cell walls of water-filled lumen, volumetric stress occurs, which leads to the development of defects known as collapse (Arganbright, 1981). Differential shrinkage occurs as a result of shrinkage anisotropy or as a result of moisture content variations in the wood when it dries. This leads to differences in shrinkage between the surface and the core of wood when the surface fibers dry first and start to shrink. While the core has not yet started to dry and shrink, and as a result, the core is preventing the surface from shrinking. Surface cracks are developed during the early stages of drying and distortion of wood (bowing, cupping, spring, and twisting). After an initial period of the drying process the core of the wood starts to dry out and try to shrink. However, the surface is permanently enlarged, which prevents the core from normal shrinkage. As a result, the stresses are reversed, with the core in tension and the surface in compression. These conditions of wood lead to internal tension pressures and induce internal checks, or honeycombing.

Arganbright (1981) described 15 types of drying defects, namely surface checks, end checks and splits, honeycombing, warp, collapse, case-hardening, reverse case-hardening, knot checking, loose knots/knot fall out, unset pitch, blue stain, brown stain, planer split, chipped and torn grain, and raised grain. On the other hand, Rasmussen (1961) and Simpson (1991) classified wood drying defects based on the sources of defects. Drying defects were divided into three categories by Rasmussen (1961) (Table.1) while Simpson (1991) divided them into four categories, including.

- Rupture of wood tissue (Surface Checks, End Checks and Splits, Collapse, Honeycomb, Loose Knots, Checked Knots, Boxed-Heart Splits, and Ring Failure)
- Warp (Cup, bow, crook, twist, and diamonding)
- Discolouration (Sapwood discolorations and Heartwood discolorations)
- Uneven moisture content (Board Rejects and Water Pockets)

According to Simpson (1991), the interplay of wood properties with handling factors causes defects in any of the above classes. Defects associated with disagreeable colour, lopsided moisture content, and unwelcome surface texture are caused by cell structure and chemical extractives in wood. The most essential processing element is the drying temperature, since it may be liable for wood defects.

There are many wood drying defects that happen during seasoning (Table.1). Commonly, these defects arise from an irregular shrinkage in longitudinal, tangential, or radial directions of wood, or in core and surface of wood, effects of micro-organisms (fungi or bacteria), and chemical substances in wood. An understanding of how, where, and when wood defects happen, will allow the worker to minimize these defects. Kiln and air seasoning are often responsible for drying defects, but in air drying, major defects can be minimized by changing stacking procedures while in kiln seasoning, by changing drying conditions.

Table 1.1 Classification of seasoning defects by Rasmussen (1961)

Drying defects classes	**Defects**	**Reason**
Shrinkage	Surface Checks	• Found on the flat sawed faces of wood in the wood rays. • The wood surfaces dry fast due to the high temperature and low relative humidity condition. Thin and narrow timber is less prone to surface check than thick and wide timber.
	End Checks	• End checks are seen in wood rays, but only on end-grain face. • When fibers rupture owing to excessively low relative humidity, water evaporates considerably quicker in the longitudinal direction than in the transverse direction.
	End Splits	• End splits refer to the rupture of fibers, extending from face to face. • All end splits are not drying defects because end split can occurs either by growth

		stresses of tree or extension of end checks during wood drying process.
	Collapse	• Collapse refers to distortion of wood cells due to compressive drying pressures on the inner sections of the wood that above the wood's compressive strength.
	Honeycomb	• Tensile failure across the grain causes internal checks, which most commonly occur in the wood rays.
	Ring Failure	• Found in either within or parallel to the annual ring. • External ring failure caused by end grain failure in the early stages of drying that grows in depth and length as drying progresses. • Internal ring failure can also occur due to weakening of the connection between annual rings as a result of high temperatures and case hardening defects.
	Boxed-Heart Splits	• Due to differential in tangential and radial shrinking of the wood surrounding the pith.
	Warp	• Due to variations in radial, tangential, and longitudinal shrinkage.
	Checked Knots	• In the wood rays, the checks occur on the terminal grain of knots during the early phases of drying due to the variations in

		shrinkage inside the knots and are exacerbated by adopting an extremely low humidity.
	Loose Knots	• During the drying process, encased knots (also known as black or dead knots) will always release. This is owing to the fact that they are fail to grow to the surrounding wood and rely only on bark and pitch to keep them in place. The board shrinks considerably in width but very little in length.
	Case-hardening	• Hardening of surface- The unavoidable outcome of shrinkage-related drying pressures, which persist even when the wood is evenly dry (Tarvainen *et al.,* 2006). • Defined as "Case hardening is a feature of dried wood that causes it to deform into a cup shape after re-sawing and equalizing the moisture content" (Ranta-Maunus *et al.*, 2001).

2.9 Drying Schedules

Haque (2002) stated that, the drying schedule comprises series of temperatures, relative humidity, and associated equilibrium moisture contents of raw timber that vary with either the actual average moisture content of the timber known as moisture content based schedule or the time since the start of drying which know as time-based schedule. Many scholars have tried designing optimal schedules using drying modelling and simulation techniques (Phonetip, 2019).

In the past, kiln drying schedules were developed through trial and error method. Following that, more logical techniques to kiln drying schedule optimization were used. Simulations that have just been viewed as the changeability of final moisture levels were used to design optimised kiln drying schedules (Cronin *et al.*, 2003). Continuous kiln drying schedules have also accounted for stress, strain, and checking/cracking (Booker, 1994). Salin (1988) carefully fostered a streamlined drying schedule for spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) for drying in batch and progressive. The drying process was also formulated by Carlsson and Esping (1997) for optimization problems that were found in previous research work. Using data on wood properties, Pordage and Langrish (2000) created a kiln drying schedule but the excess difficulties in upgrading kiln drying schedule incorporate getting adequate information on the fluctuation of wood properties, as well as optimising both to prevent cracking and to decrease the range of final moisture levels.

The methods for developing the drying schedule has not yet been extensively investigated, thus most of the researchers used existing schedules (suggested in the "Dry kiln operator's manual" or "Dry kiln schedules for commercial woods- temperate and tropical"- based on algorithm) to test their samples (Bedelean, 2017). As an example, Simpson and Steve (1997) developed an optimized kiln drying schedule for tropical and temperate hardwood using specific gravity while Klitzke and Batista (2008) and Jara *et al.* (2008) developed optimized kiln drying schedule for *Eucalyptus dunnii, Populus alba* L. lumber (7 cm thickness) and *Swietenia macrophylla* King. respectively. However, in 1965, Japanese scientist Terazawa, (1965) proposed a method for easy determination of kiln drying schedules of wood. Based on his methodology, several researchers developed specific kiln drying schedules for different species with the help of Madison schedule table. Ofori and Brentuo (2010) investigated about drying characters and drying schedules of the wood of *Alstonia brionei, Antrocaryon micraster, Bombax buonopozense*, *Dialium aubrevillei* and *Sterculia rhinopetal* based Terazawa method as well as Jankowsky (1992), Effah and Kofi (2014), Listyanto *et al.* (2010; 2016) and Appiah-Kubi *et al.* (2016) also adopt Terazawa method.

Methodologies for developing drying schedules for coconut palm wood have not yet been studied. Only Mukundan *et al.* (2019) used the Terazawa method to standardize the kiln drying schedule of coconut palm wood based on density. She measured and scored the degree of defects such as warping instead of honeycombing and collapse, which occurs during quick drying tests. The coconut wood drying schedule was predicted on a higher degree of warping, but actually there is no score chart for warping in the Terazawa method.

In order to better understand the effects of drying schedules on time, quality, energy consumption and mechanical characteristics of various wood species, studies have been undertaken by Wang *et al.* (2007). However, there hasn't been a comparison study of the coconut wood drying schedule and effects of drying schedule. Even though there are a limited number of articles that provide a general drying schedule for coconut palm wood, none of them provide authentic data regarding its methodology. According to Bailleres *et al.* (2010), during the early stages of kiln drying of coconut wood with a thickness of 25 mm, the drying temperature should not exceed 49°C and the relative humidity should be kept high (78%), to scarcely avoid surface checks or interior checks (honeycombing). Boone *et al.* (1988) recommended a kiln drying schedule, initial dry bulb temperature of 60°C with 75% relative humidity for both 25 mm and 50 mm thickness, but its final temperature of 25 mm and 50 mm should not exceed 77°C and 71°C respectively and also suggested that the direct kiln drying method is unsuitable for 50 mm coconut wood. Before kiln drying, the 50 mm coconut wood should be air seasoned up to 35% moisture content. The time base kiln schedule developed by

Palomar and Siopongco (1998) for 25 mm and 50 mm thickness, starting with 49°C and 45°C (initial dry bulb temperature), relative humidity kept at 78% and 55%, final temperature should not exceed 60°C and 65°C, and the time taken to complete the process was 37 days and 66 days respectively. Like Boone *et al.* (1988), he suggested that per-air drying is required for 50 mm before direct kiln drying for up to 14 days, but not suggested for 25 mm board. Killmann and Fink (1996) recommended a convection drying schedule with initial dry bulb temperature 50°C for both 25 mm green and 50 mm samples with above 30% moisture content.

Table 1.2 Characteristics of kiln drying schedules of Coconut palm wood

<table>
<tr><th rowspan="2">NO</th><th rowspan="2">Thickness</th><th rowspan="2">Number of steps in the schedule</th><th rowspan="2">Initial moisture content (%)</th><th colspan="2">Temperature of air (°C)</th><th colspan="2">Relative humidity of air (%)</th><th rowspan="2">Target MC (%)</th><th rowspan="2">Remarks</th><th rowspan="2">Source</th></tr>
<tr><th>Initial</th><th>Final</th><th>Initial</th><th>Final</th></tr>
<tr><td rowspan="2">1</td><td>…</td><td>9</td><td>60-45</td><td>45</td><td>80</td><td>43</td><td>6</td><td>…</td><td>General schedule for HD</td><td rowspan="2">(Mukundan et al., 2019)</td></tr>
<tr><td>…</td><td>12</td><td>110-70</td><td>50</td><td>80</td><td>38</td><td>6</td><td>…</td><td>General schedule for LD</td></tr>
<tr><td>2</td><td>25 mm</td><td>7</td><td>> 85</td><td>49</td><td>60</td><td>78</td><td>55</td><td>8</td><td>Specific kiln schedule for HD flooring</td><td>(Bailleres et al., 2010)</td></tr>
<tr><td>3</td><td>…</td><td>8</td><td>60</td><td>38</td><td>71</td><td>…</td><td>…</td><td>…</td><td>General Time based schedule</td><td>(Brion, 1984) - Philippine</td></tr>
<tr><td rowspan="3">4</td><td>25 mm</td><td>5</td><td>> 100</td><td>60</td><td>77</td><td>…</td><td>…</td><td>14</td><td rowspan="2">General Time based schedule</td><td rowspan="3">(Killmann and Fink, 1996)- successfully applied in Zamboanga, Philippine</td></tr>
<tr><td>50 mm</td><td>6</td><td>> 30</td><td>50</td><td>71</td><td>…</td><td>…</td><td>14</td></tr>
<tr><td>50mm</td><td>1</td><td>40-30</td><td>50</td><td>50</td><td>…</td><td>…</td><td>9</td><td></td></tr>
</table>

	25 mm	2	< 130	50	55	…	…	6	General schedule for HD and MD	
	50mm	2	40-30	55	65	…	…	6	General schedule for LD	
	25 mm	2	40-30	65	70	…	…	6		
5	25 mm	4	> 100	60	71	75	95	18	General schedule	(Boone *et al.*, 1988)
	50 mm	4	30-25	60	71	75	95	19		
6	25 mm	6	>85	49	60	78	43	…	General Time based schedule	(Palomar and Siopongco, 1988)
	50 mm	6	64-54	45	56	55	53	…		
7	25mm	4	> 100	60	77	…	…	…	General Time based schedule	(Haas and Wilson, 1985)- Recommended by The New Zealand Forest Service, Forest Research Institute
	50mm	4	30-25	60	71	…	…	…		

2.10 Fundamental principles of kiln drying

The fundamental principles (air temperature, relative humidity, and air circulation) of kiln drying to assure the drying uniformity and satisfy processing technology requirements with least drying defects. Controlling these principles is essential for successful and efficient drying. It is very important to apply optimal temperature, relative humidity and air circulation conditions on time of kiln drying. Uncontrolled drying (air seasoning) causes defects that can have a negative impact on the product's durability and profitability. However, both very fast and slow drying processes can develop drying defects and risk of stain respectively. In addition, the slow drying process might be costly because of time and energy consumed in kiln drying. That’s why the scholars and wood industrialists are seeking for optimal drying schedule (Bergman, 2021).

2.10.1 Temperature

With a steady relative humidity, drying will be faster as the temperature increases. Temperature affects the rate of drying by increasing the relative humidity of the air, as well as the rate of water diffusion through the wood. The temperature measured by a conventional thermometer that is freely exposed to the air but insulated from radiation and moisture in the kiln is known as dry-bulb temperature, whereas the temperature read by a thermometer wrapped in water soaked cloth is known as wet bulb temperature (adiabatic saturation temperature) (Stull, 2011). The condition of the humid in kiln is determined by combining the dry bulb and wet bulb temperatures in a Mollier chart or Psychrometric diagram (Barenbrug, 1947) and difference in these temperature (dry and wet bulbs temperature) is known as wet-bulb depression, and it is used to calculate relative humidity and less relative humidity is indicated by a larger difference between the dry-bulb and wet-bulb temperatures (Walker, 2016). Walker (2016) suggested that to avoid air stagnation inside the chamber, there must be at least a 2 m/s flow of air when air flows over a wet sleeve, the water vaporizes and the sleeve cools.

2.10.2 Relative Humidity (RH)

Saiu (1995) defined relative humidity as "the partial pressure of water vapour divided by the saturated vapour pressure at the same temperature and total pressure". Relative humidity is inversely proportional to the temperature. In other words, the amount of water vapour in the air is generally expressed as a percentage (%) of the amount required for saturation at the same temperature.

2.10.3 Air Circulation Rate

In order for wood to dry evenly in an oven, it is essential to have constant air circulation. Wood drying will be faster at constant temperature and relative humidity as the speed of air circulation increases (Wengert, 2016). Faster drying rates are not always ideal for some woods, which have a tendency to develop defects more quickly (Walker, 2016). Lower heat transfer efficiency is not a problem if moisture mobility within the wood is limited (Pordage and Langrish., 1999).

2.11 Coconut palm wood flooring

Tongue and Groove flooring (T&G flooring), Parquetry Flooring (PF), and Engineered Overlay Flooring (also known as Engineered Wood Flooring (EWF)) are the most common types of wood flooring available on the market. T&G and parquetry flooring are solid wood types of flooring that fit through the edge to edge using the tongue of one sample and the grove of another. The main distinction between these floors is the difference in sample dimensions. Another type of flooring is EWF, which is a multilayer composite product. The EWF shell is protected from dimensional changes by gluing cross structure wood panels together.

Janka-hardness is a measure of species suitability, particularly for flooring. A low Janka-hardness rating indicates that the wood is easily indented by pressure and has a high scratch probability. In general, Janka-hardness of wood (teak) above 1000ibs is best for flooring. When comparing Janka-hardness of teak with coconut, it is shown that coconut wood has high pressure resistance: average resistance of 10,950N radially and 10,800N tangentially at MC of 12%. (Haas and Wilson, 1985).

In terms of physical, mechanical, and decorative properties, coconut palm wood is one of the best appropriate materials for flooring. Recently, some study has been conducted to realise the natural wood property and processing towards a high-quality product for flooring, particularly in palm trees. The traffic level determines the choice of wood species for flooring. Mohmod and Tahir (1990) conducted a study on the suitability of palm trees for flooring purposes. He discovered that coconut palm wood (high-density) was suitable for flooring in high traffic areas due to its density and shear, but it is also classified as medium and low traffic in terms of wear resistance and hardness. Fathil *et al.* (2014) pursued similar work in which they investigated the potential use of palm tree wood for load-bearing. He observed that the mechanical strength of coconut palm wood was greater than that of oil palm and date palm, Recently, coconut palm wood flooring products were successfully developed for the Australian (target MC 9–14%) and European markets (target MC 7–11%) (Bailleres *et al.*, 2010).

3. MATERIALS AND METHODS

3.1 Study location

The study was conducted in the Forest Products and Utilization laboratory, College of Forestry, Kerala Agricultural University, Vellanikkara. Several properties such as Moisture content, Basic density, and Drying behaviour of coconut palm wood were investigated through standard procedures.

3.2 Conversion and Sampling

A mature west coast tall coconut tree of 11 m height was felled and cross-cut into 3m (9feet) logs. The drying behaviour was then determined using the basal part of the coconut tree. The flat-sawn boards were made by tangentially cutting with a portable band saw. Flat-sawn boards with thicknesses of 25 mm and 50 mm were selected from the log's periphery; called the high-density group (A). While flat-sawn boards with thicknesses of 25 mm and 50 mm were selected from the log's mid-cross-section; called medium density group (B) (Fig. 2.1).

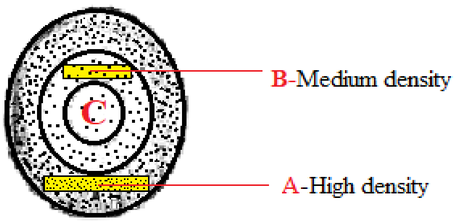


Figure 2.1. Cross section of coconut palm tree

Medium and high-density boards were cut to 10 cm in width and 210 cm in length from selected flat-swan boards. Thus, four distinct types of boards were created (25 mm and 50 mm thick high-density and 25 mm and

50 mm thick medium-density boards). Each board was cut into ten sections, with lengths alternating between 20 cm (Section A) and 22 cm (Section B). Section B (22 cm) was also cut into 20 cm (Section A) and 2 cm (Section Y). Section Y was selected to the right of Section B (Figure 2.2). All Y sections were used to calculate density and moisture content, while the remaining sections (20 cm) were used for quick drying tests.

For the quick-drying test, four sets of experimental units were chosen, each containing ten samples of coconut palm wood. Two were in the high-density category, with a thickness of 50 mm named HDC50T and a thickness of 25 mm named HDC25T, and the other two were in the medium-density category, with a thickness of 50 mm (MDC50T) and a thickness of 25 mm named HDC25T (MDC25T).

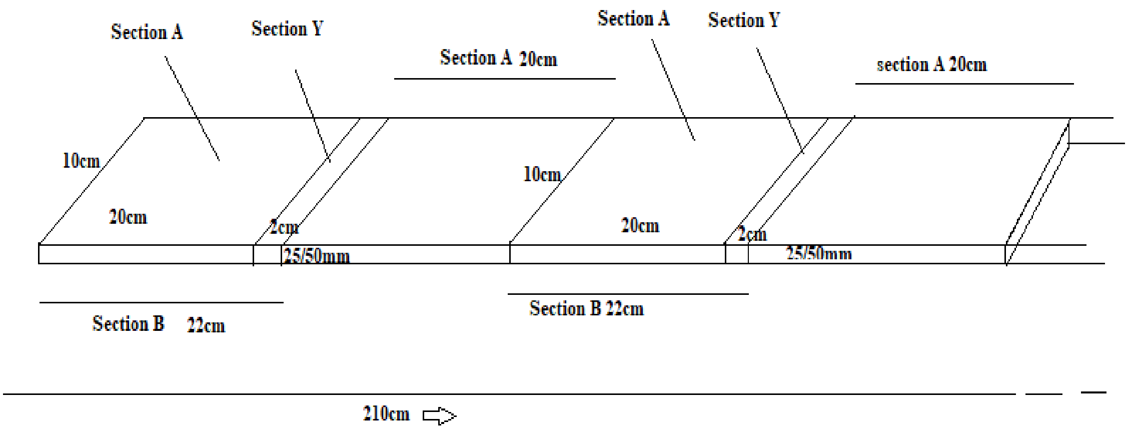


Figure 2.2. Selection of samples from flat-sawn board

3.3 Moisture content and Basic density of wood

To determine the moisture content and density of wood, three small samples with dimensions of 2 cm × 2 cm in length and width were chosen from each section of the Y part (one from the middle and the other two from the edge portion (Fig. 2.3).

The small samples were soaked in water for 1 hour and the wet weight (W_W) of each sample was measured. The volume of each sample was then calculated using the water displacement method, which involved filling a container with water and placing it on a digital balance with a precision of 0.01 gm. After that, the balance was reset to zero. The sample was then thoroughly immersed in water until it was completely submerged. The sample was forced underwater with a fine needle to ensure that the sample is free of the container's sides and bottom. The volume of the sample is equal to the measured weight of the displaced water. The samples were oven-dried at 103±2°C until they reached a constant weight (Wo oven-dry weight) and kept in a desiccator with desiccant (Silica gel used as a desiccant) to keep the samples dry. The samples were weighed immediately after removal from the desiccator and the moisture content and density of the samples calculated by using the formula.

$$MC(\%) = [(Ww - Wo)/Wo] \times 100 \quad \text{……………………….. (1)}$$

Density (kg/m^3) = Oven dry mass/Volume of wood sample………… (2)

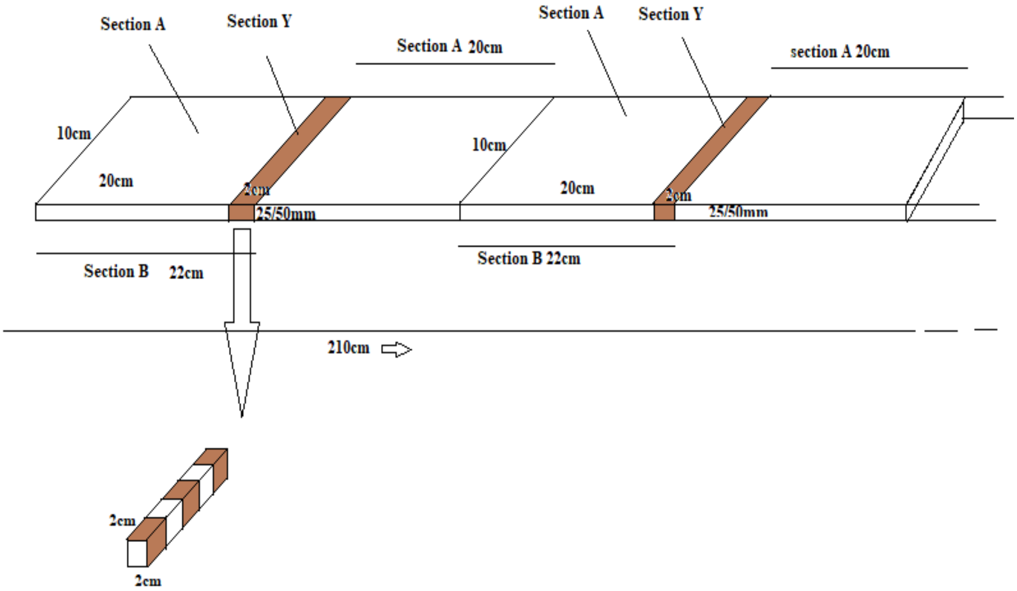


Figure 2.3. Selection of small samples for moisture content and density calculation from flat-sawn board

3.4 Quick drying test (Terazawa, 1965)

The samples were placed edgewise in an oven at 103±2°C until they were completely oven dried. Every hour for the first 8 hours, each specimen was taken from the oven for weight measurement and initial drying defect evaluation (end and surface checking). The same method was used to assess weight and defects at the 24th and 30th hours of the second day, as well as the 48th hour (third day). The measurements and observations were repeated until the sample weight was constant. The drying defects of the samples were compared using Terazawa's criterion (1965). The specimens were given scores based on the drying defects classification and subsequently based on the control parameters such as the initial dry bulb temperature (DBT), initial wet-bulb depression (WBD) and final dry bulb temperature (WBT) determined from the table prescribed by Terazawa (1965).

3.4.1 Evaluation of drying defects

A scale of 1 to 8 was used to evaluate initial checks and deformation (Table 2.1 and Table 2.3), while a scale of 1 to 6 was used to evaluate honeycombing (Table 2.2). The condition of maximum defects was compared to the checking criteria established by Terazawa (1965) and the samples were subsequently given a corresponding score based on the classification.

The above method has an inherent drawback in that the warping defects are not taken into account when developing the drying schedules, and therefore the schedules developed may not be entirely flawless and the schedules may be inefficient to prevent warping defects.

The novel approach used in this study addresses the aforementioned issue. Rasialy (1993) classified wood defects into different classes based on the severity of defects developed during the drying process (Jara *et al.,* 2008). The Rasialy classifications were used to quantify the intensity of the warping defects that develop during quick-drying tests. Therefore, in this study, the classification methods of Terazawa (1965) and Rasialy (1993) were combined to evaluate drying defects.

3.4.2 Method for evaluation of initial check

The weight and drying defects of each test sample were measured at one-hour intervals for the first 8 hours of drying in order to evaluate initial defects that evolved during the early stages of drying. The same procedure was repeated after the 24th, 30th and 48th hours of drying to determine the weight and defects. The measurements and observations were repeated until the samples reached a constant weight. Finally, the degree of initial checks was assessed on the basis of Terazawa's criteria modified by Jankowski (1992) (Table 2.1).

Table 2.1. Score attributed to the magnitudes of the checks presented in the samples subjected to quick drying test based on Terazawa (1965) and modified by Jankowski (1992)

	Checks	
Level of defects	**End checks (mm)**	**Surface check (mm)**
1	No checks	No checks
2	SC, L < 10 , W< 0.8	SC, L<50W<0.5
3	SC, L >10, W< 0.8	SC to MC, L<100 W>5 W<1 W>1
4	MC, L < 10 W>0.8, W<1.5	MC to LC, L<150 W<1.5
5	MC to LC, L > 10 W>0.8, W<1.5	LC, L>150 W>1.5
6	LC, L > 10 W< 1.5	LC, L>150 W>1.5
7	LC, L > 10 W< 1.5	LC, L>150 W>1.5
8	LC, L > 10 W< 1.5	LC, L>150 W>1.5

L= Check length, W = Check width, SC= Small checks, MC=Medium Checks, and LC=Large Checks

3.4.3 Method for evaluation of honeycombs

Once the test samples had reached a constant weight, they were cross-cut in the middle to determine the degree of honeycombing. The size and number of honeycombs on the newly exposed surfaces were recorded based on the classification of the degree of honeycombing (Table 2.2).

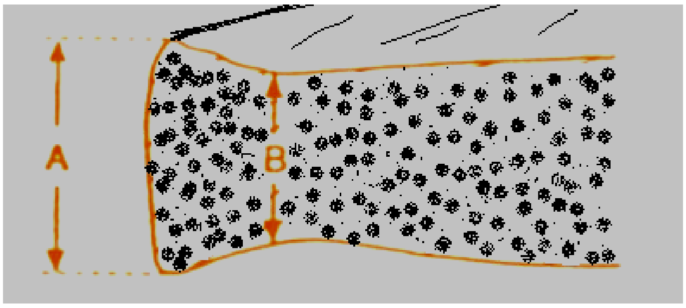
Table 2.2. Classification of degree of honeycomb (Internal checks)

Class	**1**	**2**	**3**	**4**	**5**	**6**
Degree of internal check	No check	1 WC 2 NC	2-3WC 4-5 NC 1 WC &3 NC	4-5 WC 9 NC 1 WC & 4-6 NC	6-8 WC 15 NC 4 WC & 6-8 NC	15-17 WC or Continuous checks

WC=Wide checks, NC Narrow Checks

3.4.4 Method for evaluation of deformation

Using a Digital Calliper, the thickness at points A and B along the four edges of the two halves (newly exposed surface) was measured, and the differences between the thickest (A) and thinnest (B) sizes for each of the four positions were calculated. Based on the prescribed classification, the mean values of the four differences, the thickest and thinnest (A-B) at the edge of each sample were assessed and classified as a cross-sectional deformation (Figure 2. 4; Table 2.3).



A: The portion thickest at the edge,

B: The portion thinnest 1-2 *cm* apart from the edge

Figure 2.4. Method for evaluating deformation on the section

Table 2.3. Method adopted for Classification of degree of deformation on the section

Degree	1	2	3	4	5	6	7	8
A-B(mm)	0-0.3	0.3-0.5	0.5-0.8	0.8-1.2	1.2-1.8	1.8-2.5	2.5-3.5	Over 3.5

3.4.5 Method for evaluation of warping (warpage)

The warping defects were measured and classified based on the Rasialy classification (1993) and used to supplement the deficiencies in the Terazawa method (1965).

3.4.5.1 Rasialy classification of warping defects

1. Twisting- Deflection of diagonally opposite corners from plane of board 0 mm to 0.05 cm = slight, 0.51 cm to 1 cm = medium and > 1 cm = high

2. Cupping - Deflection of edge from plane of surface 0 mm to 0.2 cm = slight, 0.21 mm to 0. 5 cm = medium and >0.5 cm = high

3. Bowing- Deflection of ends of boards 0 mm to 0.5 cm = slight, 0.51cm to 1 cm = medium and >1 cm = high

4. Crook - Deflection of edge of board 0 mm to 0.5 cm = slight, 0.51cm to 1 cm = medium and >1 cm = high

3.5 Determination of Initial DBT, Initial WBD and Final DBT

The respective drying parameters, such as Initial DBT, Initial WBD, and Final DBT were chosen from the predetermined chart (Table 2.4) prescribed for the level of checks, deformation, and honeycombing after determining the highest scores of defects (defects degrees) for various experimental units.

Table 2.4. Classification of Initial DBT, Initial WBD and Final DBT based on level of checks, deformation and honeycombing

Variety of defect	Drying condition	Defect degrees							
		1	2	3	4	5	6	7	8
Checks	Initial DBT °C	70	65	60	55	53	50	47	45
	Initial WBD°C	6.5	5.5	4.3	3.6	3	2.3	2	1.8
	Final DBT °C	95	90	85	80	80	80	80	80
Deformation	Initial DBT °C	70	66	58	54	50	49	48	47
	Initial WBD°C	6.5	6	4.7	4	3.6	3.3	2.8	2.5
	Final DBT °C	95	88	83	80	77	75	73	70
Honeycomb	Initial DBT °C	70	55	50	49	48	45	-	-
	Initial WBD°C	6.5	4.5	3.8	3.3	3	2.5	-	-
	Final DBT °C	95	83	77	73	71	70	-	-

3.5.1 Selection of schedules for Moisture content, Dry-bulb temperatures and Wet-bulb depression

Due to a lack of accepted schedules for coconut palm wood general flooring purposes in Indian zone IV (most of Kerala, including this climatic zone), the moisture content, DBT, and WBD were chosen to obtain suitable schedules by considering high-density coconut palm wood under the hardwood category and medium-density coconut palm wood under the softwood category. Based on critical condition parameters such as initial and Final DBT, Initial WBD, and Initial MC, the corresponding schedules were chosen from the table prescribed by F.P.L. in Madison, U.S.A. (Simpson, 1991).

3.5.1.1 Steps for selection of schedule for high-density coconut palm wood

A. Determination of moisture grade from Table 2.6 (for example, if the initial moisture content is 65%, this corresponds to "C" grade moisture content).

B. Determination of moisture classes from Table 2.7 with respective selected moisture content grades (For example, moisture range (%) >35, 35, 30, 25, 20 and 15 were selected with respective grade "C", then moisture ranges were converted to moisture classes like (I= Initial moisture) I -35, 35-30, 30-25, 25-20, 20-15 and <15).

C. Determination of wet-bulb depression from Table 2.7 based on initial moisture content, moisture grade, and initial WBD. (For example, If the sample belongs to the "C" grade and initial moisture above 35%, then choose the wet-bulb depression step number "1" (see Table 2.7). Select the Wet-bulb depression schedules from table 7 that correspond to the selected wet-bulb depression step number denoted above wet-bulb depression schedules).

D. Determination of dry-bulb temperature schedule from Table 2.5 with respect to the initial moisture content, initial DBT and final DBT (For example, if initial moisture content > 30%, initial DBT 50 °C and final DBT 80°C, then Dry-bulb temperatures for various temperature schedules is T6).

E. The Madison code for the above example is T6-C1.

3.5.1.2 Steps for selection of schedule for medium-density coconut palm wood

A. Determination of moisture grade- Refer 3.5.1.1 (A).

B. Determination of moisture classes from Table 2.8 with respective selected moisture content grades.

C. Determination of wet-bulb depression from Table 2.8.

D. Determination of dry-bulb temperature schedule from Table 2.5-Refer 3.5.1.1 (D).

Table 2.5. Temperature schedules with respect to moisture content for hardwood and softwood

Dry-bulb temperature step no.	Moisture content at start of step (%)	Dry-bulb temperatures for various temperature schedules													
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
1	>30	37.8	37.8	43.3	43.3	48.9	48.9	54.4	54.4	60	60	65.6	71.1	76.7	82.2
2	30	40.6	43.3	48.9	48.9	54.4	54.4	60	60	65.6	65.6	71.1	76.7	82.2	87.8
3	25	40.6	48.9	54.4	54.4	60	60	65.6	65.6	71.1	71.1	71.1	76.7	82.2	87.8
4	20	46.1	54.4	60	60	65.6	65.6	71.1	71.1	71.1	76.7	76.7	82.2	87.8	93.3
5	15	48.9	65.6	71.1	82.2	71.1	82.2	71.1	82.2	71.1	82.2	82.2	82.2	87.8	93.3

Table 2.6. Moisture content classes for various green moisture content values

Green moisture content (%)	Moisture content classes
Up to 40	A
40 to 60	B
60 to 80	C
80 to 100	D
100 to 120	E
Above 120	F

Table 2.7. Wet-bulb depression schedules for hard woods

Wet-bulb depression step no.	**MC (%)at start for various moisture content classes**						**Wet-bulb depressions for various wet-bulb depression schedules**							
	A	**B**	**C**	**D**	**E**	**F**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	>30	>35	>40	>50	>60	>70	1.7	2.2	2.8	3.9	5.6	8.3	11.1	13.9
2	30	35	40	50	60	70	2.2	2.8	3.9	5.6	7.8	11.1	16.7	19.4
3	25	30	35	40	50	60	3.3	4.4	6.1	8.3	11.1	16.7	22.2	27.8
4	20	25	30	35	40	50	5.6	7.8	10.6	13.9	19.4	27.8	27.8	27.8
5	15	20	25	30	35	40	13.9	16.7	19.4	22.2	27.8	27.8	27.8	27.8
6 and 7	10	15	≤20	≤25	≤30	≤35	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8

Table 2.8. Wet-bulb depression and moisture content schedules of range for medium density wood

Initial MC of wood (%)	**40**	**50**	**60**	**75**	**90**	**110**	**Wet bulb depression °C**							
	A	**B**	**C**	**D**	**E**	**F**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Range of MC for drying schedule	40-30	50-35	60-40	75-50	90-60	110-70	2	2	3	4	6	8	11	
	30-25	35-30	40-35	50-40	60-50	70-60	2	3	4	6	8	11	14	17
	25-20	30-25	35-30	40-35	50-40	60-50	3	5	6	9	11	14	17	22
	20-15	25-20	30-25	35-30	40-35	50-40	5	8	8	11	14	17	22	22
		20-15	25-20	30-25	35-30	40-35	8	11	11	14	17	22	22	22
			20-15	25-20	30-25	35-30	11	14	14	17	22	22	22	22
				20-15	25-20	30-25	14	17	17	22	22	22	22	22
					20-15	25-20	17	22	22	22	22	22	22	22
						20-15	22	22	22	22	22	22	22	22
	<15	<15	<15	<15	<15	<15	30	30	30	30	30	30	30	30

3.6. Determination of Relative Humidity (RH) and Equilibrium Moisture Content (EMC)

Using the tables provided in the Dry Kiln Operator's Manual under the United States Department of Agriculture (Simpson, 1991), relative humidity and equilibrium moisture content corresponding to DBT and WBD were determined.

3.7. Modification from base kiln drying schedule (Madison kiln drying schedule) to experimental kiln drying schedule for different types of coconut palm wood flooring

To obtain satisfactory experimental kiln-drying schedules, the warping defect of coconut palm wood was considered following a quick-drying test. If wood samples are classified as having the highest warp, the kiln drying schedule is treated as a special case, and the base schedule conditions are altered by abating 10% of Initial DBT, 15% of Initial WBD, and 5% of Final DBT (proposed by Terazawa). If the wood samples are classified as having slight or medium warps, the wood lumber should be properly stacked and end-coated to reduce warping defects during drying.

3.8. Equalizing and Conditioning

The final stage of the kiln drying process is equalising and conditioning. All samples were not dried evenly, and the final moisture content of the samples varied significantly. This posed significant challenges in subsequent work. Equalizing is a treatment used to prevent unequal final moisture content and to stabilise the specified moisture content of end products.

Equalizing treatment conditions is part of the schedule development process. The treatment conditions can be determined based on our desired equilibrium moisture content of the wood samples (product moisture content). The equilibrium moisture content of wood for general flooring in

Kerala should be 12%. Moisture content for flooring is also permissible if the average moisture content of a wood lot is within 15% and individual samples are within 14% (IS 287-1993). Equalization can be accomplished by increasing WBT and relative humidity while maintaining the same final DBT. Conditioning aids in the alleviation of residual compression stresses in the wood surface through plasticization with high DBT and relative humidity. Conditioning should, in general, work after equalising treatment. This also aids in achieving uniform EMC in all areas of the wood.

3.8.1 Equalizing procedures

a) Begin equalizing when the driest kiln sample has an average moisture content that is 2% less than the desired final average moisture content.

b) Adjust the schedule operation to achieve 12% EMC by increasing the WBT and relative humidity (Select the WBD and RH at the final DBT from the table prescribed by F.P.L. (Simpson, 1991) to help achieve 12% EMC).

c) Continue equalizing until the wettest and driest samples have equalised to 12% EMC.

3.8.2 Conditioning procedures

a) Reduce the average desirable EMC by 4% at the same or higher final DBT.

b) If the desired EMC is 12%, then choose the WBD and RH at the final DBT from the table prescribed by F.P.L. (Simpson, 1991) to help reduce 4% MC and achieve 8% EMC.

4. RESULT

This section contains the results of basic density analysis, moisture content, and drying tests of coconut palm wood are provided based on a series of experiments.

4.1 Basic density (kg/m^3) and Moisture content (%)

The basic density of experimental units HDC50T, HDC25T, MDC50T and MDC25T was 700∓92 kg/m^3, 700∓66 kg/m^3, 550∓40 kg/m^3 and 550∓30 kg/m^3, respectively. The average moisture content was 45.40% for HDC50T, 43.25% for HDC25T, 75.10% for MD50T and 81.17% for MDC25 with mean basic density of 691.88 kg/m^3, 731.17 kg/m^3, 586.33 $kg/m^3$and 554.56 kg /m^3, respectively.

The basic density of coconut palm wood was classified into two categories: HDC50T and HDC25T above 600 kg/m^3 were considered high-density, and below 600 kg/m^3 up to 400 kg/m^3 were considered medium-density (MDC50T and MDC25T). As a result, the HDC50T and HDC25T experimental kiln schedules were recommended not only for tongue and groove flooring but also for parquetry flooring. At the same time, the MDC50T and MDC25T schedules are only suitable for engineered overlay flooring.

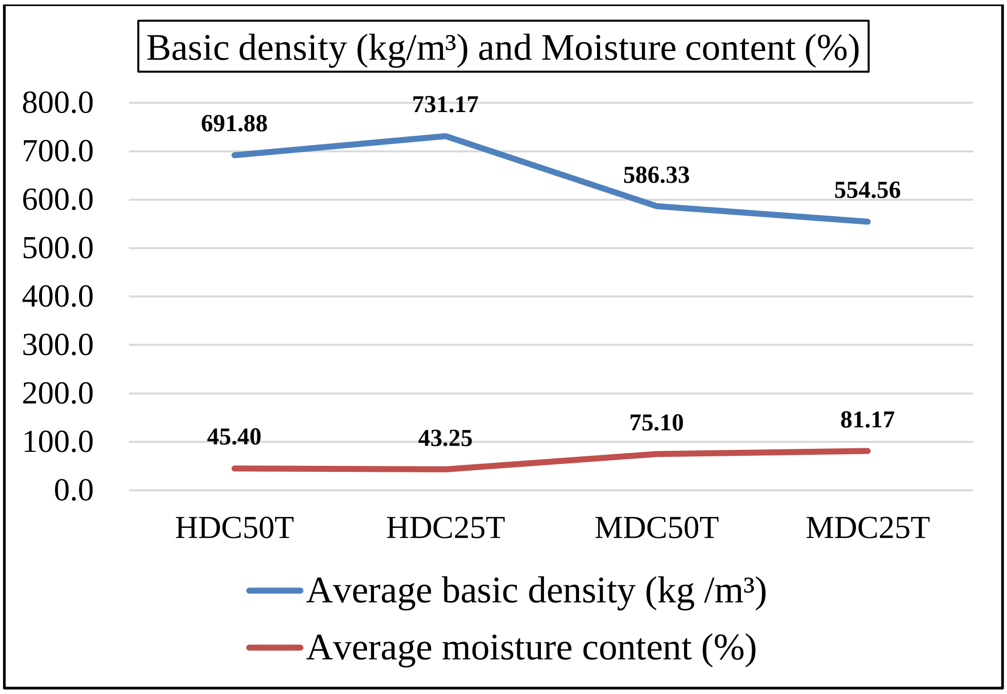


Figure 3.1. Basic density (kg/m³) and Moisture content (%) of Coconut palm wood samples

4.2 Drying rate of coconut palm wood during quick drying test

At the beginning of the quick-drying test, the slope of the MDC25T graph shows a significant amount of water loss per unit time. Similarly, MDC50T has a sloping pattern similar to MDC25T. Due to the high moisture content of medium-density woods, water loss was significant during the initial drying phase. The slower the drying rate, the heavier the wood. Furthermore, the amount of water loss is proportional to the thickness of the wood sample, implying that the amount of water loss is also affected by the thickness of the timber.

The behaviour of the drying curves presented by medium-density and high-density differed since the first hour of the test, as shown in Figure 3.2. The MDC25T samples reached a moisture content of 16 % fast (Fig. 2). This could be because medium-density coconut palm wood has medium basic density and higher initial moisture content.

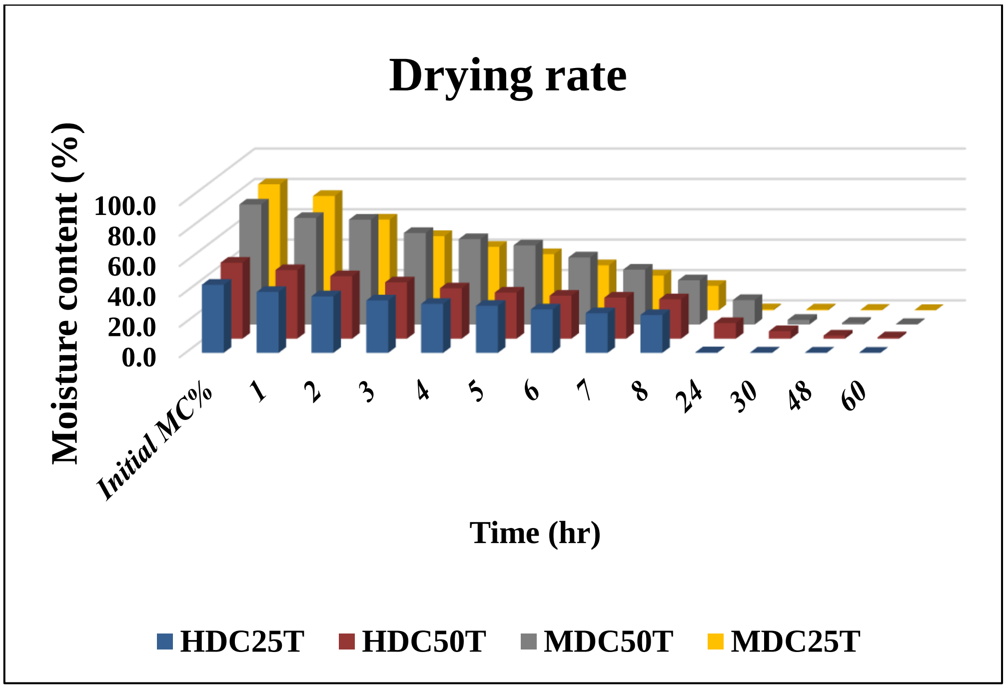


Figure 3.2. Drying rate of experimental units in oven dry at 103±2°C

4.3 Quick drying test

The degree of defects of experimental units during the quick-drying test was shown in Tables 3.1, 3.2, 3.3 and 3.4. The highest defect score in each experimental unit was used to develop base kiln-drying schedules (starting structure for further modification). The Rasialy classification of warping defects (1993) was used to modify the base kiln-drying schedules and finalise the experimental kiln drying schedule. The following are the key findings from the quick drying test.

4.3.1 Degree of surface checks and end checks in HDC50T experimental unit

Throughout the quick-drying test, surface checks were one of the most conspicuous defects. However, the higher asperity of surface checks was most likely to be observed during the initial stage of drying (1^{st}h to 8^{th}h). Surface checks become unobtrusive at the end of the drying test period. The highest degree of the surface check was 8, which was discovered during the 5th hour of quick-drying testing in the 4th sample. Only 30% of HDC50T samples had the most severe defects, while 20% of samples had less severe defects (Table 3.1).

Another significant defect was discovered during the quick-drying test: end checks, found in 70% of the samples. The highest and lowest end check ranks were found to be 6 and 4, respectively. The fifth sample had the highest degree of end checks during the 6th hour (Table 3.2).

Plate 3.1. End check observed during initial stage of quick drying test of 25 mm thick medium-density coconut palm wood

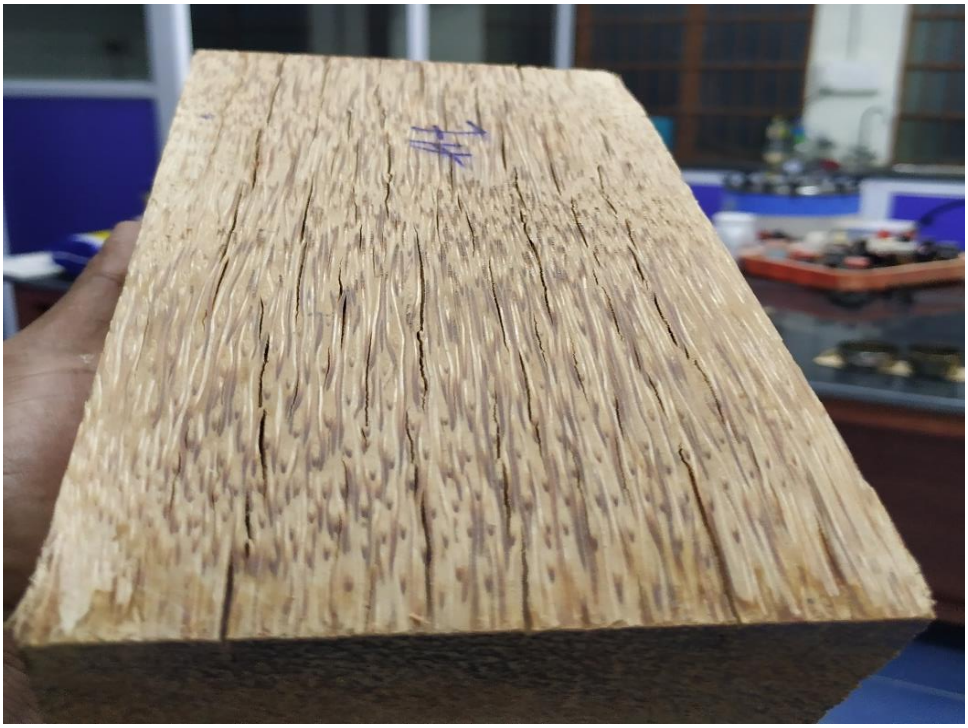


Plate 3.2. Surface check observed during initial stage of quick drying test of 50 mm thick high-density coconut palm wood

Table 3.1. Degree of surface checks of experimental unit HDC50T observed during quick drying test

TIME	SURFACE CHECKS									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1sth	1	1	1	1	1	1	1	1	1	1
2ndh	3	5	3	4	5	3	3	3	3	3
3rdh	4	5	3	5	3	4	4	3	3	4
4thh	4	5	4	5	3	4	5	3	4	4
5thh	4	6	4	8	4	4	5	3	4	5
6thh	4	8	4	8	4	4	8	4	4	5
7thh	6	8	4	8	4	4	8	4	4	5
8thh	6	8	5	8	4	4	8	4	5	6
24thh	5	6	3	6	4	4	4	4	5	5
30thh	5	3	3	5	3	3	3	4	4	5
48thh	4	3	3	5	3	3	2	4	4	5
Rank	6	8	5	8	5	4	8	4	5	6
OVERALL HIGHEST SCORE : 8										

Table 3.2. Degree of end checks of experimental unit HDC50T observed during quick drying test

TIME	END CHECKS									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1sth	2	1	1	1	2	2	0	2	2	2
2ndh	2	2	2	2	2	2	2	2	2	2
3rdh	3	4	5	3	2	3	2	2	3	4
4thh	3	4	5	3	5	3	2	2	3	4
5thh	3	4	5	3	5	3	5	5	3	5
6thh	3	4	5	4	6	5	5	5	4	5
7thh	4	6	6	6	6	6	6	5	4	5
8thh	4	6	5	5	6	6	6	5	5	6
24thh	4	4	5	5	6	6	4	5	5	6
30thh	3	4	5	4	5	5	3	4	5	5
48thh	3	4	5	4	4	5	3	4	5	5
Rank	4	6	6	6	6	6	6	5	5	6
HIGHEST SCORE : 6										

4.3.2 Degree of surface checks and end checks in HDC25T experimental unit.

The highest surface check degree was 6, which was discovered in the second, fifth, and sixth samples during the eighth hour of quick testing. Only 30% of HDC25T samples had the most severe defects (6), with the remaining 30% having less severe defects (Table 3.3).

The end checks did not have a noticeable appearance in HDC25T samples. Ninety per cent of the samples received a score of less than a five. The highest and lowest end check ranks were found to be 5 and 3, respectively. The highest degree of end checks was only detected in the sixth sample at the sixth hour (Table 3.4).

Table 3.3. Degree of surface checks of experimental unit HDC25T observed during quick drying test

TIME	**SURFACE CHECKS**									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1st h	1	1	1	1	1	1	1	1	1	1
2nd h	1	1	2	1	1	2	1	1	1	1
3rd h	2	2	2	2	2	2	2	2	2	2
4th h	2	2	2	2	2	2	2	2	2	2
5th h	2	2	2	2	2	2	2	2	2	3
6th h	4	3	2	3	2	3	2	2	2	3
7th h	4	3	3	3	3	4	4	4	4	2
8th h	3	6	2	3	6	6	4	4	4	2
24th h	3	3	3	3	3	3	3	3	3	3
30th h	2	2	2	2	2	2	2	2	2	2
48th h	1	1	1	1	1	1	1	1	1	1
RANK	4	6	3	3	6	6	4	4	4	3
HIGHEST SCORE : 6										

Table 3.4. Degree of end checks of experimental unit HDC25T observed during quick drying test

TIME	END CHECKS									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1st h	1	1	1	1	1	1	1	1	1	1
2nd h	1	1	1	1	1	1	1	1	1	1
3rd h	1	1	2	1	1	2	1	2	1	1
4th h	3	2	2	2	2	3	2	2	2	2
5th h	3	2	4	3	2	2	2	2	2	2
6th h	3	2	4	3	3	5	3	3	3	3
7th h	3	3	4	3	3	3	3	3	3	3
8th h	3	3	4	4	3	3	3	3	3	3
24th h	2	2	2	2	2	2	2	2	2	2
30th h	2	2	2	2	2	2	2	2	2	2
48th h	2	2	2	2	2	2	2	2	2	2
RANK	3	3	4	3	3	5	3	3	3	3
HIGHEST SCORE : 5										

4.3.3 Degree of surface checks and end checks in MDC50T experimental unit

The highest degree of surface check was 7, and only 20% of MDC50T samples had the most severe defects (Table 3.5), whereas 40% of the samples had a high degree of end check. The highest and lowest end check rankings were discovered to be 6 and 4, respectively (Table 3.6).

Table 3.5. Degree of surface checks of experimental unit MDC50T observed during quick drying test

TIME	SURFACE CHECKS									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1st h	1	1	1	1	1	1	1	1	1	1
2nd h	1	1	1	1	1	1	1	1	1	1
3rd h	1	1	1	1	1	1	1	1	1	1
4th h	2	5	5	2	2	2	2	2	2	2
5th h	2	4	5	3	3	3	3	2	3	3
6th h	3	4	5	3	3	4	5	2	3	3
7th h	4	5	6	3	3	7	4	5	4	5
8th h	4	6	5	7	4	7	4	5	4	6
24th h	5	5	5	7	4	6	4	5	4	6
30th h	5	5	5	7	4	7	4	5	4	6
48th h	5	5	5	7	4	7	4	5	4	6
RANK	5	6	6	7	4	7	5	5	4	6
HIGHEST SCORE : 7										

Table 3.6. Degree of end checks of experimental unit MDC50T observed during quick drying test

TIME	END CHECKS									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1st h	0	0	0	0	0	0	0	0	0	0
2nd h	1	1	1	1	1	1	1	1	1	1
3rd h	1	1	1	1	1	1	1	1	1	1
4th h	1	1	1	1	1	1	1	1	1	1
5th h	2	2	2	2	2	3	2	2	2	2
6th h	5	3	3	3	2	3	3	2	3	3
7th h	5	6	3	6	3	3	5	2	4	4
8th h	5	6	6	6	4	4	5	4	4	6
24th h	5	6	6	5	4	4	5	4	4	6
30th h	5	6	6	5	4	4	5	4	4	5
48th h	5	6	5	5	4	4	5	4	4	5
RANK	5	6	6	6	4	4	5	4	4	6
HIGHEST SCORE : 5										

4.3.4 Degree of surface checks and end checks in MDC25T experimental unit

The highest level of surface checks was 7, discovered only in the seventh sample during the eighth hour of quick-drying testing. Only 10% of the MDC25T samples had the most serious defects, while 30% of the samples had the least serious defects (Table 3. 7). Unlike the HDC50T samples, the end checks in the MDC25T samples had a distinct appearance. The samples with the highest degree of end check (6) account for half of the total, with the remaining samples ranked as five or lower (Table 3.8).

Table 3.7. Degree of surface checks of experimental unit MDC25T observed during quick drying test

TIME	SURFACE CHECKS									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1^{st}h	0	0	0	0	0	0	0	0	0	0
2^{nd}h	0	0	0	0	0	0	0	0	0	0
3^{rd}h	1	1	1	1	1	1	1	1	1	1
4^{th}h	1	1	1	1	1	1	1	1	1	1
5^{th}h	1	1	1	1	1	1	1	1	1	3
6^{th}h	3	3	3	3	3	3	3	3	2	3
7^{th}h	4	4	4	4	3	4	4	4	2	4
8^{th}h	5	5	6	4	5	4	7	4	3	4
24^{th}h	4	4	5	4	5	4	5	4	4	5
30^{th}h	4	4	5	5	5	4	5	4	4	5
48^{th}h	4	4	5	5	5	4	5	4	4	5
RANK	5	5	6	5	5	4	7	4	4	5
HIGHEST SCORE : 7										

Table 3.8. Degree of end checks of experimental unit MDC25T observed during quick drying test

TIME	END CHECKS									
	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1st h	0	0	0	0	0	0	0	0	0	0
2nd h	0	0	0	0	0	0	0	0	0	0
3rd h	2	2	2	2	2	2	2	2	2	2
4th h	2	2	2	2	3	2	2	3	2	2
5th h	3	3	3	3	3	3	3	3	3	3
6th h	6	5	4	4	5	5	5	3	3	3
7th h	6	5	4	4	5	6	5	5	4	5
8th h	6	6	5	5	5	6	6	5	4	6
24th h	5	5	4	5	5	5	5	5	4	6
30th h	5	5	4	5	5	5	5	5	5	6
48th h	5	5	4	5	5	5	5	5	5	6
RANK	6	6	5	5	5	6	6	5	5	6
HIGHEST SCORE : 6										

4.3.5 Degree of honeycombing and deformation in experimental units

After quick-drying testing, honeycombing and deformation were observed. Honeycombing had the highest degree of 4 in all experimental units except MDC25T, while deformation had the highest degree of 6, which was only observed in MDC50T (Table 3.9).

Table 3.9. Degree of Honeycombing and Deformation in experimental units observed after quick drying test

DEFECTS	SAMPLES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	HDC50T									
HONEYCOMBING	3	3	3	3	3	3	3	2	2	4
DEFORMATION	3	3	3	3	4	4	4	3	3	3
	HDC25T									
HONEYCOMBING	2	2	3	2	3	3	4	3	3	2
DEFORMATION	2	1	1	1	2	2	2	2	2	2
	MDC50T									
HONEYCOMBING	3	4	3	3	2	4	3	4	3	4
DEFORMATION	5	5	5	3	6	3	5	5	6	6
	MDC25T									
HONEYCOMBING	0	0	0	0	0	2	0	0	0	0
DEFORMATION	1	1	1	1	1	1	2	1	1	1

4.3.6 Degree of warping defects in experimental units.

Unequal shrinkage and expansion (Warping) were prominent in all samples. According to Rasialy (1993), the warping effect was classified as high, medium, or slight. There are four major categories of warping defects (Cupping, Bowing, Twisting or Winding, and Crook), with twisting or winding being the most noticeable defect in all experiment units (Table 3.10). The most significant observation in this part was only winding (twisting) classified as high-level, while all others were classified as slight level. The intensity of the most prominent warping defect (winding) was used to update the Terazawa method-based drying schedules (base kiln schedule). This revision to the base drying schedule will provide adequate support to reduce the warping of the coconut lumber.

Table 3.10. Classification of Twisting defects in experimental samples observed after a quick drying test.

Experimental units	**Samples**										**Classification status**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
HDC50T	1.2	2.2	1.3	2.5	0.9	0.9	2.3	0.8	1	1.2	High
HDC25T	0.5	1.7	2.6	2.1	1.9	1.6	1.9	1.2	1.3	2.2	High
MDC50T	1.7	1.1	2.0	2.6	1.9	2.3	1.3	1.7	1.6	2.0	High
MDC25T	0.5	1.0	0.6	0.6	0.5	1.3	0.6	0.6	0.7	1.4	High

Slight= 0.0-0.5 cm, Medium= 0.51-1 cm, High= >1 cm

4.4 Determination of base kiln drying schedules (use as the foundation experimental kiln drying schedules) for further modification

Table 3.11 displays the consolidated results of the quick-drying test (except warping result), which includes the maximum score obtained for each defect based on Terazawa's criteria as modified by Jankowski (1992). These drying defects correlate with pre-determined critical drying parameters such as Initial DBT, Initial WBD, and Final DBT and their corresponding Madison kiln-drying schedule code developed for each coconut palm wood experimental unit. The surface check was high severe in all experimental samples during the early stages of the quick-drying test. Meanwhile, as the quick-drying test progressed, these defects became less conspicuous.

Critical drying conditions with respect to the adopted score of the experimental unit are given in Table 3.11. The table indicated that the experimental unit HDC50T should begin drying at 45°C (initial DBT) and progress to 80°C (final DBT) with an initial WBD of 1.8°C. The HDC25T unit on the other hand, should be between 50 and 80°C, with a 2.3°C temperature difference between Initial DBT and Initial WBT. MDC50T and MDC25T should dry from 47°C to 80°C, with an initial WBD of 2°C.

The base kiln-drying schedule has been developed based on moisture content and critical conditions of each unit. The base kiln-drying schedule T4-B1 (Table 3.12), T6-B1 (Table 3.13), T6-D2 (Table 3.14) and T6-E1 (Table 3.15) were used for the further updation by considering warping defects classification.

Table 3.11. Summary of initial moisture content and adopted classification of defect types used in proposing the critical drying condition and its suitable corresponding Madison kiln drying schedule

Experimental units	Average MC%	Highest Score obtained				Adopted Score	Proposed critical drying condition based on adopted score			
		Surface checks	End checks	Honeycomb	Deformation		Initial DBT℃	Initial WBD℃	Final DBT ℃	Corresponding Madison kiln schedule code
HDC50T	45.4	8	6	4	4	8	45	1.8	80	T4-B1
HDC25T	43.3	6	5	4	2	6	50	2.3	80	T6-B2
MDC50T	75.1	7	6	4	6	7	47	2	80	T6-D1
MDC25T	81.2	7	6	2	2	7	47	2	80	T6-E1

Table 3.12. Base kiln drying schedule (Madison kiln drying schedule) of 50 mm high-density coconut palm wood

Code:T4-B1					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM%**
>35	43	2	41	87	18
35-30	49	2	47	86	18
30-25	54	3	51	86	17
25-20	60	6	54	73	11
20-15	60	14	46	46	7
<15	80	28	52	26	3

Table 3.13. Base kiln drying schedule (Madison kiln drying schedule) of 25 mm high-density coconut palm wood

Code:T6-B1					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM%**
>35	50	2	48	88	17
35-30	54	2	52	88	16
30-25	60	3	57	87	15
25-20	66	6	60	74	10
20-15	66	14	52	48	7
< 15	80	28	52	26	3

Table 3.14. Base kiln drying schedule (Madison kiln drying schedule) of 50 mm medium density coconut palm wood

Code:T6-D2					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM %**
75-50	47	2	45	88	17
50-40	47	3	44	85	16
35-30	47	5	42	74	12
30-25	55	8	47	64	10
25-20	60	11	49	54	8
20-15	66	14	52	48	7
(‘)	66	17	49	41	6
-	66	22	44	28	4
-	66	22	44	28	4
<15	80	30	50	24	3

Table 3.15. Base kiln drying schedule (Madison kiln drying schedule) of 25 mm medium density coconut palm wood

Code : T6-E1					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM%**
90-60	47	2	45	88	18
60-50	47	3	44	85	16
50-40	47	5	42	74	12
40-35	47	8	39	61	10
35-30	47	11	36	48	8
30-25	55	14	41	43	7
25-20	60	17	43	38	6
20-15	66	22	44	28	4
-	66	22	44	28	4
<15	80	30	50	26	3

4.5 Modification of base kiln drying schedule (Madison kiln drying schedule) to experimental kiln drying schedule for different types of coconut palm wood flooring

In order to obtain a satisfactory experimental kiln drying schedule, the warpage of coconut palm wood was considered after a quick-drying test. The base schedule T4-B1 of the HDC50T unit was modified to MT4-B1 (Table 3.16) schedule by abating 10% of initial DBT, 15% of initial WBD and 5% of final DBT. Similarly, the same percentage of drying conditions were reduced from T6-B1, T6-D2 and T6-E1 and updated to MT6-B1, MT6-D2 and MT6-E1 (Table 3.17, Table 3.18 and Table 3.19) respectively. The deduction of 15% initial WBD was negligible in all cases. Equalization and conditioning treatment conditions were applied on the Madison kiln drying schedule then modified as earlier mentioned, then again made equalization and conditioning treatment conditions by changing RH and WBT with respective Final DBT and Final EMC.

The high-density coconut palm wood schedules MT4-B1 for 50 mm thickness and MT6-B1 for 25 mm thickness may aid in the production of defect-free lumbers for tongue-and-groove and parquetry flooring. Meanwhile, the medium-density coconut palm wood schedules MT6-D2 (50 mm thick) and MT6-E1 (25 mm thick) can be used to produce defect-free lumbers for engineered overlay flooring.

4.6 Experimental kiln drying schedules

The experimental kiln drying schedule with Initial DBT 39°C (Relative humidity (RH) 89 %), Initial WBD 2°C, and Final DBT 57°C was the most recommended for tongue-and-groove flooring and parquetry flooring, However, for 25 mm thick high-density coconut palm wood (HDC25T) for tongue-and-groove flooring and parquetry flooring schedule associated with Initial DBT 45°C (Relative humidity (RH) 90%), Initial WBD 2°C and Final DBT 62°C was prescribed as the most effective experimental schedule.

The most recommended experimental kiln drying schedule for 50 mm thick high-density coconut palm wood tongue-and-groove flooring and parquetry flooring was the schedule with Initial DBT 39°C (Relative humidity (RH) 89 %), Initial WBD 2°C, and Final DBT 57°C, whereas for 25 mm thick high-density coconut palm wood (HDC25T) for tongue-and-groove flooring and parquetry flooring schedule associated with Initial DBT 45℃ (Relative humidity (RH) 90%), Initial WBD 2℃ and Final DBT 62℃ were prescribed as the most effective experimental schedule.

Table 3.16. Experimental kiln drying schedule of 50 mm high density coconut palm wood for tongue-and-groove flooring and parquetry flooring

Code : MT4-B1					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM%**
>35	39	2	37	89	19
35-30	49	2	47	86	18
30-25	54	3	51	86	17
25-20	60	6	54	73	11
Equalizing	57	8	49	64	12
Conditioning	57	19	38	52	8

Table 3.17. Experimental kiln drying schedule of 25 mm high density coconut palm wood for tongue-and-groove flooring and parquetry flooring

Code : MT6-B1					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM%**
>35	45	2	43	90	19
35-30	54	2	52	89	17
30-25	60	3	57	84	14
25-20	66	6	60	74	10
Equalizing	62	8	54	60	12
Conditioning	62	13	49	54	8

Table 3.18. Experimental kiln drying schedule of 50 mm medium density coconut palm wood for engineering overlay flooring

Code : MT6-D2					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM%**
75-50	42	2	40	87	18
50-35	47	3	44	85	16
35-30	47	5	42	74	12
30-25	55	8	47	64	10
Equalizing	57	8	49	64	12
Conditioning	57	19	38	52	8

Table 3.19. Experimental kiln drying schedule of 25 mm medium density coconut palm wood for engineering overlay flooring

Code : MT6-E1					
MC%	**DBT°C**	**WTD°C**	**WBT°C**	**RH%**	**EM%**
90-60	42	2	40	87	18
60-50	47	3	44	85	16
50-40	47	5	42	74	12
40-35	47	8	39	61	10
Equalizing	45	8	37	60	12
Conditioning	45	9	36	50	8

5. DISCUSSION

5.1 BASIC DENSITY AND MOISTURE CONTENT

5.1.1 Key findings

After a thorough examination of wood density, it was discovered that the difference between the maximum and minimum density values in 50 mm thick high-density coconut palm wood was 189 kg/m^3. The large density variation in a single sawn board may cause severe drying defects. It's reasonable to expect that the large density variation can be one of the reasons for the high susceptibility of drying defects in the HDC50T (the highest degree of defects was 8) experimental samples. In the case of 25 mm thick density (HDC25T) wood samples, the density variation was comparatively less than HDC50T. The density range of MDC50T experimental unit samples shows both medium and high-density categories, but its average value is under the medium category. However, the density variation in this board is not as much as in high-density category wood. The initial moisture content calculation is used to establish the schedule of moisture classes. The initial moisture class of HDC50T and HDC25T ranged from green to 35%. MDC50T and MDC25T were 75%-50%, and 90%–60%, respectively.

5.1.2 Comparison with previous studies

The moisture content of examined samples shows a similar pattern found in previous studies conducted by Kloot (1952), Richolson and Swarup (1977), Killmann (1983), and McGavin *et al.* (2019). Results indicate that a trend of low moisture content for high density wood and high moisture content for medium density wood. Moisture content varies according to the number of parenchymatous cells and fibre bundle caps. The moisture content of coconut palm wood increases with stem height as well as from the periphery to the centre, primarily due to the non-homogeneous nature of coconut palm wood (Killmann, 1983; Richolson and Swarup (1977).

5.2 DRYING RATE

Analysis of the drying rate in experimental units revealed that the drying rate depends upon both the density and thickness of the sample. The results depicts an abnormal drying pattern in the MDC50T samples at the initial stage which cannot be true in practice (Fig 3.2). The source of this anomaly could be a power outage. A general drying pattern of woods can also be seen in high-density wood samples. The drying rate of medium-density 25 mm thick wood samples was faster than the other experimental units. The overall drying rate indicates that coconut palm wood dries quickly in nature, reaching 16% moisture content from 81% within the first 8 hours of quick drying of 25 mm thick medium-density coconut palm wood.

5.3 METHODOLOGY AND DRYING DEFECTS

5.3.1 Methods, limitations and new approach

The classifications of Terazawa (1965) and Rasaily (1993) were used to assess the degree of drying defects in coconut palm wood. Despite their popularity, the methods have some limitations in that they cannot cover all drying defect manifestations. The Terazawa method has a significant flaw in that it is silent on the classification of warping and other defects (case-hardening and compression failure). For adjusting the schedule condition, As per Jara’s suggestion, Rasaily (1993) classification was used to test the performance of the kiln drying schedules (Jara *et al.,* 2018). However, the Rasaily's (1993) classification also has the disadvantage that it cannot quantify the degree of adjustment in schedule conditions. A novel approach was introduced here to address the aforementioned issues. The schedule was developed using Terazawa's criteria, and warping effects were investigated using the Rasaily method (rather than analysing samples from the kiln drying machine, we examined samples from the quick-drying test), and the schedule was finally adjusted based on warping effects using simple adjustment criteria proposed by Terazawa in his study.

5.3.2 Comparison with previous studies

The most common drying defects in coconut palm wood are checks (surface and end), warping (cupping, bowing, twisting or winding, and crook), internal checks (honeycombing), and deformation (cross-sectional spool-like deformation). Except for Mukundan *et al.* (2019), no previous research has been conducted on the manifestation of drying defects in coconut palm wood. In their study, medium-density (20 mm thick) wood had a score of 7 and high-density (20 mm thick) wood scored 6. However, in the present study, high-density wood drying defect scores were 8 (for 50 mm thick) and 6 (for 25 mm thick), and medium-density wood scored 7. The study Mukundan (2019) claimed that medium-density wood is more susceptible to drying defects than high-density wood, but the present study found the opposite in the case of 50 mm thick high-density wood versus 50 mm thick medium-density wood. As previously stated, the large density variation in a single sawn board is the primary cause of this inconsistency. The 25 mm thick high and medium-density board follows a normal trend (medium-density wood is more susceptible to drying defects than high-density wood). The number of parenchymatous cells and vascular bundles in wood may explain this. The preceding argument is also in agreement with Brown (1998).

5.3.3 Reason for the drying defects

In our study, the most common defects were twisting and checks. The drying defects can be related to drying stress due to the differential shrinkage and hydrostatic tension. Surface checks were caused by rapid shrinkage of the coco-wood surface at its weakest point, but end checks were caused by rapid moisture loss from the end surface rather than the inner region of the wood (here, the tension stresses are near the end face and compression stresses are inside the wood samples). The tension stress in the core region at the end of drying (reverse stress) causes the development of honeycombs

(Internal-checks). Differential shrinkage in longitudinal, radial, and tangential directions contributes to warps. The collapse is caused by internal crushing under high stress (Hydrostatic tension) and inward rupture of cell walls due to the extreme temperature.

5.3.4 Recommendations to mitigate the drying defects

The above-mentioned drying defects can be controlled and reduced by using a suitable drying schedule and providing favourable drying conditions. The warping defects can be controlled by wood treat with high final moisture content and lowering the Initial DBT, Initial WBD, and final DBT, as well as proper stacking and arrangement of the wood sample. Surface and end checks can be controlled or eliminated by pausing the initial DBT but increasing the WBD to some extent and low initial DBT with high relative humidity conditions prevents the checks. End coating could also be considered as a preventive method of end checks. The intensity of the drying rate of wood determines all other defects. Uniform gradual drying of wood by gradual increasing DBT and WBD will help to make defect-free lumber. In the case of collapsed wood in extreme conditions, the reconditioning process (steaming treatment-100°C, 100 % RH) can aid in 50% collapse recovery.

5.3.5 General idea on a selection of schedules

If a specific wood sample fails the quick-drying test with a high degree of defect, it must be treated with less severe drying schedules. If the sample had the fewest defects, it could be subjected to a more severe schedule. A similar pattern of results was obtained in this study. When compared to other experimental units, the high density 25 mm thickness coconut palm wood (HDC25T) schedule MT6-B1 showed more severe than other coconut palm wood schedules because the wood sample unit was less susceptible to defects (highest score was 6) during the quick-drying test. The high susceptibility to defects found on HDC50T (highest score of 8) assuages the drying schedule.

5.4 KILN DRYING SCHEDULE OF COCONUT PALM WOOD

5.4.1 Findings, limitations of previous studies and scope of the study

This section discusses practical considerations, potential avenues for future research, and general findings. The following experimental kiln-drying schedules (Tables 3.16 to 3.19) for various flooring purposes in different thicknesses are suggested here, which correspond to the modified FPL Madison schedules: 50 mm thick high-density Tongue-and-groove flooring [MT4-B1], 50 mm thick high-density parquetry flooring [MT4-B1], 25 mm thick high-density Tongue-and-groove flooring [MT6-B1], 25 mm thick high-density parquetry flooring [MT6-B1], 50 mm thick medium density engineered overlay flooring [MT6-D2], and 25 mm thick medium density engineered overlay flooring [MT6-E1]. All developed schedules are moderate entail with high initial humidity and modest temperature conditions (less than 50°C), which can be employed for kiln drying to prevent drying defects. Except for Bailleres *et al.* (2010), all previously published coco-wood kiln-drying schedules are generalised to any purpose. In addition, there are no published articles on coconut palm wood kiln-drying schedules for flooring, particularly concerning the Indian climatic zone.

Overall schedule results demonstrate the potential superiority over the schedules established by other scholars. This argument is based on two main points. First, Mukundan *et al*. (2019) used similar approaches previously, but their investigations were not validated for schedule development. The downside with their approach was that the warping defects were not considered in the Terazawa method. The second major reason is that the schedules are available but do not overwhelmingly support the schedules due to a lack of data on the procedure of development of schedule and also all schedules are not suitable to Kerala condition.

In this study, the DBT temperature recommended for 40 % moisture content of 25 mm thick medium-density coconut palm wood was 47°C, but

Killmann and Fink (1996) recommended 65°C for similar sample. The above results are inconsistent with Killmann and Fink (1996) results. The reason for such a disparity in results is that the present study developed drying schedules using standard methodology as well as novel approaches. This demonstrates that thorough applications of the recommended schedule as per this study may provide a more desirable outcome than Killmann and Fink proposed schedule (1996).

The development of more rigorous methods other than simple methods is required in wood rheology. Coconut wood is highly anisotropic. Along and across the coconut palm wood, the moisture content and density gradients are high. This least deform in wood. The present results can be used as a reference for future studies to establish the wood drying defects and drying stress relationship of coconut more in-depth. It would be beneficial to understand what exactly happens in coconut palm wood. Furthermore, the experimental kiln-drying schedules in this study could be refined further by taking into account the potential of kiln drying schedules to produce defect-free materials.

Another application of the research findings is that the drying schedules of coconut palm wood can be used in different climatic zones after equalising and conditioning schedules in the prescribed moisture content for end-use. Kerala falls under the fourth moisture content zone; average annual relative humidity of more than 67%. The moisture content of coconut wood should be kept at 12% for better general flooring performance, called equilibrium moisture content of coconut palm wood (ISI: 287-1993).

5.4.2 Supportive evidence from previous works

The experimental schedule of 25 mm thick high density in our study was MT6-B1which agrees with the schedule developed by Bailleres *et al.* (2010) for industrial production of defects free 25 mm thick high-density coconut palm wood flooring lumber.

All previous general schedules of 50 mm and 25 mm thick high-density coconut palm wood are more severe (see Table 2) than the schedules developed in this study. The schedule MT4-B1 and MT6-B1 may perform better than other schedules because coconut palm wood is fast-drying in nature, so it should be treated with a moderate drying schedule. The schedule MT6-D2 with DBT 47°C at a moisture content range of 30%-35% agree with Killmann and Fink (1996) proposed schedule conditions of initial DBT 50°C at a moisture content of 30-40% for 50 mm medium density wood that was successfully applied in Zamboanga, Philippine.

6. SUMMARY

The coconut tree, which is common in Kerala, has great potential for marketing flooring because of its density, stability, and durability, which are comparable to common flooring hardwood species. Suitable drying conditions make the wood stronger and durable. Therefore project's goal was to create critical kiln conditions that would allow coconut palm wood to be sound and stable under natural environmental conditions. The key findings are summarised below.

1. Basic density (kg/m^3) - The basic density of experimental units High-density 50 mm thick coconut palm wood (HDC50T), High-density 25 mm thick coconut palm wood (HDC25T), Medium-density 50 mm thick coconut palm wood (MDC50T) and Medium-density 25 mm thick coconut palm wood (MDC25T) was 700 ∓ 92 kg/m^3, 700 ∓ 66 kg/m^3, 550 ∓ 40 kg/m^3 and 550 ∓ 30 kg/m^3, respectively.

2. Moisture content (MC%)- The mean moisture content was 45.40% for HDC50T, 43.25% for HDC25T, 75.10% for MDC50T and 81.17% for MDC25 with mean basic density of 691.88 kg/m^3, 731.17 kg/m^3, 586.33 kg/m^3 and 554.56 kg/m^3, respectively. The MC (%) decreases with increasing basic density.

3. Drying rate - The heavier the wood, the slower the drying rate. Medium-density coconut palm wood dries quickly, reaching 16 % moisture content from 81 % after 8 hours of extreme drying conditions.

4. Twisting and surface checks were the most dominant defects in both high-density and medium-density coconut palm wood, whereas the wood was least susceptible to honeycombing and deformation.

5. Equalizing treatment conditions of schedules were selected based on the desirable product Equilibrium MC (12%). Equalizing treatment conditions will help to avoid unequal final moisture content in wood.

6. Conditioning treatments were selected, for reducing total residual compressive stresses in the wood surface through plasticization.

7. The recommended experimental kiln drying schedule of 50 mm thick high-density coconut palm wood for tongue and groove flooring and parquetry flooring was MT4-B1 (schedule code). The critical condition of MT4-B1; Initial Dry bulb temperature (DBT) 39°C (Relative humidity (RH) 89%), Initial Wet bulb depression (WBD) 2°C and Final DBT 57°C.

8. The high-density coconut palm wood (25 mm thick) for tongue and groove flooring and parquetry flooring schedule MT6-B1 associated with Initial DBT 45℃ (Relative humidity (RH) 90%), Initial WBD 2℃ and Final DBT 62℃ was prescribed as the most effective experimental schedule.

9. The recommended engineered overlay flooring schedule for 50 mm thick medium-density coconut palm wood was MT6-D2 as follows: Initial DBT 42°C (Relative humidity (RH) 87%), Initial WBD 2°C at moisture range 75-50%, and Final DBT 57°C.

10. The schedule of engineered overlay flooring for 25 mm thickness medium-density coconut palm wood was MT6-E1, includes an Initial DBT of 42°C (Relative humidity (RH) of 87%), Initial WBD of 2°C at a moisture range 90%-60%, and a Final DBT of 45°C.

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Development of experimental kiln-drying schedules for different types of coconut (*Cocos nucifera* L.) palm wood flooring

by

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8. ABSTRACT

In India, there is a significant gap existing between supply and demand for wood and wood products. Several factors influence wood consumption. For example, the construction sector is witnessing a shift to eco-friendly furnishings. Indeed, the eco-friendly amenity of wooden flooring in hotels and houses has contributed to an upswing in commercial wood consumption. In the current scenario, effective utilisation of existing lesser-known species such as *Cocos nucifera* L. (Coconut palm tree) is gaining prominence. The lesser known wood species will help to meet the domestic demand and may help to bridge the gap between supply and demand of timber.

Seasoning of wood is a crucial step for producing defect-free timber for the ease of doing timber work and potential use of available timber. The purpose of this research is to develop experimental kiln-drying schedules for *Cocos nucifera* L. (Coconut palm tree) for various flooring methods (Tongue & Groove flooring (T&G flooring), Parquetry flooring, and Engineered overlay flooring). The substructure, base kiln-drying schedules were developed based on the Terazawa method (1965), and optimised using Rasialy (1993) classification. The critical conditions of equalizing treatment and conditioning treatment were established in relation to the product's desirable moisture content, which is 12% for general wood flooring products in climatic zone IV (Kerala).

High-density wood samples with thicknesses of 25 mm and 50 mm (20 cm x 10 cm in length and width) were used to investigate drying defects under drastic conditions, and schedules for both thicknesses were developed. Similarly, schedules were developed using medium-density wood samples of 25 mm and 50 mm. The moisture content of the experimental samples (2 cm x 2 cm in length and width) was determined using the oven-dry method, and the basic density was determined based on the water displacement method.

The experimental kiln drying schedule recommended for 50 mm thick high-density coconut palm wood Tongue and Groove flooring and Parquetry flooring was MT4-B1 (schedule code). Initial Dry Bulb Temperature 39°C (Relative humidity 89%), Initial Wet Bulb Depression 2°C, and Final Dry bulb Temperature 57°C were the critical conditions for MT4-B1. The high-density coconut palm wood (25 mm thick) is also suitable for Tongue & Groove flooring and Parquetry flooring and the schedule was MT6-B1 with Initial Dry Bulb Temperature 45°C (Relative humidity 90%), Initial Wet Bulb Depression 2°C, and Final Dry Bulb Temperature 62°C. The recommended experimental kiln drying schedule for medium-density coconut palm wood of 50 mm thickness was MT6-D2 as follows: Initial Dry bulb Temperature 42°C (Relative humidity 87%), Initial Wet Bulb Depression 2°C, and Final Dry bulb Temperature 57°C. The schedule for 25 mm thickness medium-density coconut palm wood was MT6-E1, which includes an Initial Dry bulb Temperature of 42°C (Relative humidity 87%), Initial Wet Bulb Depression of 2°C and a Final Dry bulb Temperature of 45°C. The medium-density coconut palm wood only can be used for overlay flooring because of its low strength. All the schedules are made, considering the desired moisture content (12%) for general flooring purposes under the prevailing conditions of Kerala (Relative humidity > 67%) as prescribed by the Bureau of Indian Standards (BIS).