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A Decade of Improved Lumber Drying Technology

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Abstract In this paper, we comprehensively review the relevant literature published from 2005 to 2016, focused on lumber drying and provide a summary of where we feel future research will focus. Drying is a critical part of most wood products manufacturing process, and the methods used and proper control are key to achieving the appropriate production level, quality, and costs. While a combination of drying methods may be used, most lumber is dried in a kiln at some point in the process. The most common commercial kilns can be classified as conventional, high temperature, and vacuum; however, there continues to be some interest in solar and compression drying. While no new drying technologies have been proposed, work has continued on improving the existing methods. Control of the drying process varies with the type of kiln used, the species being dried and the temperatures used in the process; however, it usually involves some type of measurement of the moisture content of the wood being dried. The development of new methods for controlling the drying process focuses on new ways to measure moisture content or moisture content variation, temperature drop across the load, and drying stresses. While wood quality can be defined differently by its various users, for example, industrial or end users, certain aspects of quality remain constant across these groups, such as minimizing warp, checks, and splits, and discoloration, and maintaining or enhancing mechanical properties. New schedules have been proposed to increase drying rate and improve drying quality. Methods to reduce drying defects and improve its quality have focused mainly on mechanical restraint to prevent warp, better understanding of defect formation, and pre-treatments to speed up the drying process or reduce final moisture content variation. Finally, concerns regarding the environmental impacts of wood drying, most importantly the high energy demands and emissions, have increased in importance as concerns about sustainability and health issues become more mainstream.

Keywords Lumber · Wood · Drying · Kiln drying · Kiln schedule · Degrade

Introduction

Most lumber must be dried prior to use since drying reduces shrinkage, increases strength, reduces weight, allows wood to be treated and adhesives to be applied, and improves overall manufacturing quality [1]. Lumber is typically dried using some combination of air-drying, accelerated air-drying or pre-drying, and kiln drying, where proper control of the drying process allows the highest quality to be attained economically. Control usually consists of the timely application of the appropriate temperature, relative humidity, and air circulation. Poor control of the drying process leads to defects that can adversely affect the value and quality of the product and higher drying costs. For example, improper moisture content in dried pine lumber can lead to losses between \$1.2 and \$2.8/m^3 and poor warp control losses between 50 and 150 dollars per thousand board feet (MBF). Several methods or

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combination of methods exist for the drying of solid wood products, and there are a variety of ways to control the drying process. Much of the recent work on drying has focused on improving the methods used to dry lumber, on improving or developing new methods of control, and on the environmental aspects of the drying process. The objective of this paper is to comprehensively review literature published during the last decade and discuss the body of work related to the methods of drying solid wood, including control of the drying process, avoidance of defects, energy consumption, and environmental issues. By disseminating recent relevant research findings, this review should help promote improved drying processes that will result in faster drying times, raw material with better quality, and improved environmental performance, outcomes that should lead to increased competitiveness for those who adopt these technologies.

Major Drying Technologies

The methods used to dry wood and to control the process vary based on species, desired moisture content (MC), size of the material, quality aspects, and economics. While air-drying is commonly used for large timbers or in combination with kiln drying at some point in the process, most lumber is dried in a kiln. Kiln drying allows the best control over the environmental conditions that promote drying. The most common kiln types are convectional steam, dehumidification, vacuum, and solar.

Conventional Kilns

The majority of softwood and hardwood lumber is dried in conventional steam-heated kilns [2]. Conventional steam kilns vary between those that are a batch process or progressive or continual process. While there has been an increase in the use of progressive kilns in the softwood industry, little research has been published over the last decade on the use of progressive kilns, other than the determination that for drying Scots pine with similar quality, a two-zone progressive kiln had lower energy consumption and drying costs than single-zone batch kilns [3]. Most hardwoods and many softwood species are dried using maximum temperatures below 100 °C, whereas some softwood species such as southern yellow pine are currently dried using temperatures higher than 100 °C. Recent work on high-temperature drying has focused on its application to sub-alpine fir [4], spruce, and pine lumber [5] to reduce drying times (up to 3.5 %) and warp. Superheated steam used in combination with hot air has been suggested as a drying method to reduce the drying time for rubberwood (by 62 %) and pitch pine compared to convectional drying and improve modulus of elasticity (MOE) [6], compression parallel to grain, and hardness [7].

Vacuum Drying

Vacuum drying differs from conventional drying in that it allows for rapid drying to occur at lower temperatures, and one of the driving forces of moving water vapor is the pressure gradient. Current research on vacuum drying has focused on comparisons of the technology to conventional drying technology, its use for different species or MCs, and the potential improvements of its abilities.

While most previous work comparing vacuum drying to conventional drying has focused on the reduction of drying times, Brenes et al. [8•] compared the ability of both to support “lean manufacturing” operations. Simulation of drying and processing operations was performed to determine that the use of vacuum drying in flooring manufacturing plants could reduce total cycle time between 78 and 90 %, work-in-process inventory by 52–57 %, leading to a potential cost savings of USD7.3–13.6 million a year [8•].

While vacuum drying is used to dry many hardwoods and softwoods, it does have some limitations when drying certain species with high green MC. Hansmann et al. [9] developed a technique to rapidly dry green *Eucalyptus globulus* with shorter drying times than conventional drying and with better quality (less cracks) [9]. Others have attempted to combine vacuum drying with different technologies to improve drying time and quality. He et al. [10] used ultrasonic energy in combination with vacuum drying to accelerate the drying process for Chinese catalpa (*Catalpa ovata*); they determined that samples treated with ultrasound had diffusion coefficients 12 to 41 % higher than untreated samples, which resulted in a 27 % faster drying rate [10]. Zhangjing and Lamb [11] explored the use of a hot water-heated vacuum-drying system to dry green red oak dimension parts at different drying temperatures. They were able to dry red oak parts from green to approximately 6 % MC within 30 h at a temperature of 50 °C and pressure of 12 mmHg with good quality [11]. A combination of low radio-frequency and vacuum contact drying was tested for birch by Lopatin et al. [12], who were able to achieve a drying rate 25 % higher than vacuum alone [12]. Elustondo et al. [13] proposed the use of radio frequency vacuum (RFV) drying as a cost-effective way to re-dry “wets” or boards that remain under-dried after conventional drying. They concluded that this strategy reduces drying time by 4.6 %, final MC variability, area shrinkage (0.51 % reduction), and degrade (increase in lumber value of USD2.8 per m^3) [13].

Solar Drying

The use of the sun’s energy to dry lumber continues to be of interest, especially as the focus on energy in manufacturing increases. However, the majority of interest and continued research on solar drying focuses on smaller volume, lower cost, or low technology solutions for drying lumber. There are many examples of new variations on old designs such as a low-cost design, easy-to-construct and operate, suited for tropical countries, especially for remote communities where electricity is scarce and expensive [14, 15]. Others have compared the indicative life-cycle embodied energy and embodied carbon values for the construction and maintenance of two different wood-drying solar kiln designs with the same timber load capacity over an assumed service life of 20 years and determined that one kiln had 37 % lower life-cycle embodied energy and 43 % lower embodied carbon values than the other [16].

Other works on solar kilns have focused on the modeling of the drying process. Solar drying in a greenhouse-type chamber with two glazed walls was modeled by Bekkiou et al. [17, 18•] with input values of temperature, MC, and relative humidity. Hasan and Langrish [17] developed a numerical simulation for the modeling of solar kilns for hardwood timber drying with different boundary conditions. The simulation was used to predict the key behavior of the wood and the kiln itself under different geographical and weather conditions [17].

A very useful review and analysis of the development of solar-heated dry kilns was completed [18•], where the authors analyzed each main component of the solar kiln. They then compared developments of each component group using eight laws of evolution. They determined that most modifications have focused on optimizing their thermal and drying efficiency. Based on the analysis, they suggest future developments should focus on the arrangement of components, use of storage with independent heating, integration of an air heater in the storage and not in the drying chamber, and management of different drying cycles according to quality control of the product [18•].

Compression Drying

Press-drying, or compression drying, is a technique where wood is subject to compression forces from heated platens, with the purpose of increasing moisture loss and reducing warp. Recent work has focused on its use for plantation wood, which contains a high percentage of juvenile wood. The effect of press drying on the mechanical properties of plantation-grown loblolly pine (*Pinus taeda*) has shown that it does not significantly change the specific gravity or bending properties, but can decrease work to maximum load under some conditions [19]. Mikkola and Korhonen [20] looked at the mechanical and structural changes caused by compression drying of Finnish pine (*Pinus sylvestris L.*) and determined that compression drying enhanced the tangential mechanical properties and surface hardness as a result of the increased latewood-to-earlywood ratio (due to earlywood deformation) [20]. Combining press-drying with other drying techniques such as drilled holes as a way to improve drying and mechanical properties has been shown to significantly increase moisture loss and reduced compressive stress for Japanese cedar (*Cryptomeria japonica*) specimens [21].

Drying Process Control

Control of the drying process is critical to achieve the highest quality with the lowest cost. Control of the drying process is done using programmable logic controllers (PLC), where the temperature, relative humidity, and air-flow are controlled by the PLC, often with a PC interface. The PC interface allows the kiln operator to manually set the environmental conditions or to have the computer automatically control the process based on time or some other monitoring input. The methods used to monitor the drying process vary greatly between the type of kiln used, the species being dried and the temperatures used in the process (low temperature versus high temperature). Common monitoring methods currently used in commercial lumber drying include the use of sample boards that are manually or automatically weighed to determine MC, the use of probes to measure electrical resistance related to MC, dielectric measurement of MC, temperature drop across the load, and time schedules. Improvements on these methods and the development of new methods focus on measuring MC or MC variation, temperature drop across the load, and drying stresses.

Measurement of Moisture Content

One of the most common methods of process control in the conventional drying of hardwoods is to set the temperature and relative humidity based on the MC of the lumber. Specific methods for this technique include the sampling of fast and slow drying material and controlling the drying process such that the slowest drying samples control the majority of the process and the fastest drying samples are used to prevent over-drying. This method can be implemented by manually or remotely weighing the samples, for which many commercial systems are currently in use; however, no systems are currently available that measure the distribution of moisture in the wood. Current research focuses on new methods to automatically measure or estimate the MC of drying lumber, which include the use of microwaves, X-rays, NIR, and vibration.

Microwave systems for MC measurement have been developed and tested in laboratory settings. Schajer and Orhan [22] developed a microwave system that measured grain angle, moisture, and density. The prototype microwave system successfully measured MCs with standard errors of 1.2 and 1.9 %, with a range between 7 and 28 % MC for hemlock (*Tsuga spp.*) and Douglas fir (*Pseudotsuga menziesii*) [22]. Moschler et al. [23, 24] developed and tested an in-kiln dielectric meter which could measure MCs from 6 to 100 %

with a standard deviation of less than 1.5 % MC. While this system showed great promise, it utilized frequencies within the range of 4.5–6 GHz, which are currently restricted for commercial use [23, 24].

Several investigators have continued to look at the use of X-rays to measure the moisture gradient in convectively dried wood. One system used a newly developed soft X-ray digital microscope to demonstrate that that X-ray imaging could be used to determine moisture gradients during drying. The technique involved comparing the oven-dry MC of samples taken at various stages in the drying process and relating it to average gray-scale values from X-ray images [25]. Similar work on moisture gradients but for vacuum drying was conducted on Norway spruce (*Picea abies*) boards at different drying times, where the theoretical uncertainty was less than 1 % for MCs below 100 % [26].

Computer tomography (CT) has been used to determine moisture gradients in wood and to further investigate how wood behaves during the drying process. For example, Hansson and Cherepanova [27] demonstrated an image-processing algorithm for investigating density, MC, and moisture loss during drying and suggested that such a system could be further developed to control the drying process [27]. Sobue and Woodhead [28] worked on a CT method for estimating moisture distribution in squared timbers and stated that the reconstituted moisture distribution matched well with that determined by the oven-dry method. However, for both research projects, no data in regard to accuracy was presented [28].

Near-infrared (NIR) radiation has been used to measure many different chemical and physical properties in wood [29], and work continues on its use to measure the MC in the drying process. NIR was successfully used to measure MC of Scots pine (*Pinus sylvestris L.*) logs using multi-step sample preparation and NIR scanning procedure, where the root mean square error of prediction was 0.8 and 10 % for heartwood and sapwood, respectively [30]. NIR has also been used to sort hem-fir timbers more successfully than with a capacitance-type moisture meter [31]. Vibration as a method for measuring MC in wood has been demonstrated such that as resonance frequencies decreased as the MC increased; however, no data or discussion about the accuracy of the method was presented [32].

Special techniques have been proposed for measuring MC during vacuum drying. One such technique uses measurement of temperature and pressure in wood to monitor MC during radio frequency vacuum (RFV) below fiber saturation point where the methods developed had an absolute error within 0.8 to 1.8 % [33]. Lui et al. [34] used the relationship between equilibrium moisture content (EMC) and temperature, relative humidity, and ambient pressure as a basis for monitoring MC under various pressures during RFV drying. They determined that as ambient pressure decreased, EMC increased more than what is indicated by Kollmann's chart. The MC estimated from temperature and pressure for Hinoki wood (*Chamaecyparis obtusa*) was smaller than the MC determined by the oven drying method. The absolute errors of their method ranged from 1.0 to 1.5 %; however, when the estimate included the modified EMC, absolute errors dropped to within 0.6 % [34].

While the use of temperature drop across a load (TDAL) for drying wood is currently used for several softwood species, efforts to develop this technique with new sensors continue. Elustondo et al. [35] suggested that when drying occurs with low evaporation, the sensors typically used in commercial kilns are not accurate enough to measure TDAL; therefore, they developed and tested a new and more accurate sensor to measure this parameter and demonstrated that TDAL could be used to estimate drying curves in conventional lumber drying [35]. They further developed and tested the system to demonstrate that the TDAL sensor can be satisfactorily used for detecting the transition point between wet and dry wood regardless of the drying process, determining the drying end-point after sensor calibration, and monitoring drying rate on the basis of airflow volume rate, lumber volume, and lumber basic density [36].

Measurement of Drying Stresses

The ability of directly or indirectly measure drying stresses has been proposed as a method to control the drying process of wood species prone to checks and splits. Research regarding new methods for measuring of drying stresses can be divided into the development of new methods to control the drying processes and for understanding the development of drying stresses. New methods include the use of acoustic emissions, direct sensor measurement, MC gradient combined with shrinkage data, and the use of NIR.

While acoustic emissions (AE) do not directly measure the stresses developed during drying, they have been suggested as a method to control the drying process as they are related to stress formation. Beall et al. [37] demonstrated that acoustic emission (AE) monitoring can lead to drying times up to 40 % shorter when drying above the fiber saturation point, compared with conventionally controlled loads [37].

Several different types of sensors that directly measure the stress in drying wood have been proposed. Allegretti and Ferrari [38] developed and tested a sensor to measure internal compressive drying stresses based on a silicon micromachined pressure gage inserted in a cylindrical Teflon shell in the wood [38]. Fe et al. [39] used Lurethane (a thermoset elastomeric polyurethane with high toughness), as a medium to transfer the pressure from wood to a pressure transducer [39]. Diawanich et al. [40] used a restrained half-sawn specimen, a restrained free shrinkage specimen, and a load cell as a real-time technique for measuring internal stress perpendicular to grain [40]. Diawanich et al. [41] used the restoring force measured from a half-sawn specimen to measure the magnitude of internal stress within the kiln-dried lumber during cooling and conditioning. They determined that cooling under relatively high humidity after drying improves the internal stress relief within kiln-dried rubberwood lumber (*Hevea brasiliensis*) during conditioning [41]. Watanabe et al. [42] demonstrated that NIR could be used to predict drying stress levels to detect critical periods in drying [42]. While all the methods described demonstrated being able to measure drying stresses to some degree, no commercial system using these techniques is yet available at the time of writing.

Other researchers have focused on measuring drying stresses to increase the understanding of their formation, knowledge that can be used to improve drying. For example, Clair [43] determined the contribution of maturation stresses to drying shrinkage. He analyzed the strains in the longitudinal and tangential planes of reference in both tension wood and normal wood and determined that part of the shrinkage is caused by the release of internal stresses during the desorption process [43]. Other attempts to use drying stress information include the use of restoring force measurements on half-sawn specimens under various patterns of wet-bulb temperature and using the information to optimize a drying schedule [44] and to estimate the drying stress by measuring the MC gradient of the surface and core layers, and the shrinkage of the board [45]. Tarmian et al. [46] used physical measurements for both longitudinal and transverse drying stress in poplar with mixed tension/normal wood to develop a schedule that results in the least amount and length of checks and warp [46].

Drying Schedules

A drying schedule is the outline of environmental conditions to control the removal of moisture until the desired MC is reached. Commonly, schedules are listed to set air temperature and humidity levels in the kiln based on time or on the MC of lumber in the kiln. New schedules are constantly being developed and tested on new or known species to dry with optimal quality, in the shortest time possible, or both. This review will not focus on schedule development for individual species but will focus on the application of new ideas in schedule development and the impact of schedules on wood quality.

While most conventional and high temperature schedules use a constant temperature and relative humidity for each step, some studies suggest that oscillating or cyclic drying conditions may reduce drying stress and possibly reduce drying times. For example, Mili et al. [47] compared conventional drying to oscillating the EMC or temperature for drying beech (*Fagus sylvatica L.*) and found less case-hardening for schedules that oscillated EMC or temperature; however, oscillations of both temperature and EMC did not reduce case-hardening [47]. De la Cruz-Lefvre et al. [48] determined that the mechano-sorptive effect, activated by MC oscillations, leads to a significant stress relaxation [48]. Rémond and Perré [49] focused their work on the oscillation frequency and stress development using simulation models and determined that 30-min oscillations reduced the average absolute stress beneath the surface by about 30 % and that longer oscillation times were less effective [49]. While oscillating drying shows some promise for reducing drying stresses, the potential for drying time reduction remains unproven.

Wood Quality

Wood quality is often defined differently depending on the material being dried, those drying the material and those using the material. However, certain aspects of quality remain constant across these groups, such as minimum warp, checks and splits, and discoloration in wood. Work to improve wood quality through drying includes the modification of schedules and techniques specific to the defect type; therefore, discussion of wood quality will be done by defect type.

Warp

Warp can be divided into four categories: cup, twist, bow, and crook. Cup is caused by differences in shrinkage in two faces of the board. Xaing et al. [50] proposed the use of a surface coating as a way to minimize warp during drying of southern red oak (*Quercus falcata*) and demonstrated that this method can be effective in reducing cup if it is applied to the pith side of the tangential face of the specimens [50]. Bow, crook, and twist are caused by longitudinal shrinkage in the wood, which is usually a result of reaction wood, spiral grain, diagonal grain, or growth stresses.

Interest in understanding, modeling, and preventing warp in softwoods has increased recently. Twist in lumber results from the presence of juvenile or reaction wood and slope of grain [51]; however, some have suggested that annual growth ring curvature has the greatest impact relative to grain angle and tangential shrinkage [52]. While some have investigated the extent of the twisting force during drying with the goal of being able to predict the force required to keep lumber from twist [53], others have successfully used mechanical restraint to reduce crook, bow, and twist [54]. These methods of warp control can increase the value of lumber between 50 and 150 US dollars per MBF. Fruhwald [55] further demonstrated that the reduction in twist by restraint was permanent during subsequent moisture variations. The lateral restraining of drying loads was also applied to reduce warp (not only twist but bow and crook) by use of a pressure bar and pneumatic cylinders [55]. Research in the reduction of warp in hardwoods suggests that lower temperature or more mild schedules lead to minimal warp [56–59].

Stacking practices have great influence on the occurrence of warp. Bond and Wiedenbeck [60] looked at how differences in stacking practices affected drying degrade, kiln capacities, and rough mill yields of red oak (*Quercus rubra*) lumber. They determined that drying degrade was not significantly different between the two trimming and stacking practices, that kiln capacity can be increased by an average of 4 to 12 % for precision end-trimmed lumber; and that using lumber with over-length leads to an increase in rough mill yield [60].

Checking and Honeycomb

Checks and honeycomb in wood are a direct result of excessive drying stresses during the process and discussion of the control and understanding of drying stresses has already been covered. However, Song and Shida [61] attempted to monitor surface checking during the drying process using NIR, and they determined that the coefficient of variation of the surface temperature increased in the checked areas of cross-section, whereas it decreased in the unchecked areas [61]. Others determined that growth site and the location of the wood within the tree greatly influenced the percentage of honeycomb or internal checking occurring during drying for radiata pine (*Pinus radiata*) [62].

Collapse

Collapse is a defect that often occurs with woods of high MC, where removal of the free water from the lumen is too rapid, which results in collapse of the cell due to capillary forces. Recent work on collapse has focused on rapidly grown plantation species and methods on how to recondition collapsed wood. When drying *Eucalyptus urophylla*, the use of an intermittent drying process (drying followed by lower temperature and higher humidity periods) decreased total shrinkage and collapse by one third, compared to a continuous drying process; however, the schedule leads to longer drying times [63]. For collapse recovery, the authors suggested using a temperature difference between the drying period and the intermittent period. A comprehensive summary of collapse and collapse prevention was provided by Goo [64]. While he focused more on plantation-grown eucalypts, the summary includes information pertinent to many hardwood species, where he concludes that collapse is largely related to the properties of the wood being dried. Only freeze-drying was demonstrated to completely avoid collapse in the species discussed. While the authors reviewed many different strategies to reduce collapse, their use by the industry is limited to those that provide the greatest benefit versus the cost. Blakemore and Langrish [65] suggested that the application of heat, rather than moisture pick-up was the most important component of the steaming reconditioning process [65].

Wet Pockets

Wet pockets are common in many commercial species, and their presence leads to increased drying times, degrade, and high variation in MC after drying; all factors reduce lumber's value and usefulness. Several methods have been developed to detect wet pockets and determine their severity. Alkan et al. [66] demonstrated that the computerized tomography (CT) scanning technology could be used to detect wet pockets in lumber [66], and Watanabe et al. [67] developed an NIR system that could work at a line speed of 0–100 mm per second and detect surface wet-pockets in kiln-dried lumber [67]. They further developed the system to include both visible and near-infrared spectroscopy to distinguish wet-pockets in normal subalpine fir (*Abies lasiocarpa*) [68].

Final Moisture Content

While the impact of air velocity on the drying rate above and below fiber saturation point in convention kiln drying is well known, several investigators looked at its effects in more detail. Steiner et al. [69] studied the effects of air velocity to determine when and how much it can be reduced without affecting the drying rate of the Norway spruce timber dried at 70 °C. They determined that too early or too sharp a reduction in air velocity results in a reduced drying rate and a large variation in MC; however, a reduction in air velocity can occur at 40 and 20 % MC, without considerable changes in the drying schedule but did result in an increase in final MC variation [69]. Vikeberg et al. [70] looked at airflow distribution in an industrial kiln and how it is affected as the fan speed is reduced. They determined that airflow distribution did not significantly change as the fan speed was reduced, and no locations where the air movement stopped were found. They also found that relatively more air ran in the bolster spaces in comparison to the adjacent packages. The application of these results is limited to the kiln types used in the experiments [70].

Stain

Stain or discoloration in wood usually results from either a fungal or a chemical reaction of components already present. Enzymatic or chemical stain in hardwood continues to be of interest to researchers. Several have confirmed that elevated temperature and liquid flow transport of solutes on the surface chemistry are shown to influence the formation of stain in maple (*Acer spp.*) [71]. A new method to prevent enzymatic stain includes the "Elder process," a patented treatment, where lumber is heated to 120 °F and wet-bulb depression near zero, followed by cooling, which resulted in significant stain reduction [72]. They estimated that the process would on average increase dry lumber value between $32/MBF and $58/MBF in red oak. Using inert gasses or oxygen-free environments during the high-temperature drying of wood to prevent stain has been successfully demonstrated in radiata pine [73] and Norway spruce (*Picea abies*) [74]. McCurdy et al. [75] used a spectrophotometer and the CIELab scale to measure surface color change during drying of radiata pine, while studying the formation of kiln brown stain. The authors concluded that color changes above and below fiber saturation, and that drying temperature is significantly correlated with color change, with color change accelerating at temperatures higher than 60 °C [75].

Effect of Drying on Color

Wood color is a critical attribute in some applications, particularly in high value-added products. As customers increasingly favor lighter colors, researchers have focused on factors that may have an impact on color and color uniformity during manufacturing. A considerable amount of work has been conducted on the impact of drying variables, such as drying temperatures and residence time, and how they influence the final color of wood. For example, Ratnasingam and Grohmann [76] studied color changes in rubberwood (*Hevea brasiliensis*) under different drying schedules and determined that discoloration increased with higher temperatures and drying time, while lower relative humidity tended to minimize discoloration. They recommended the use of lower drying temperature and relative humidity schedules to minimize discoloration of rubberwood [76].

Mottonen and Karki [77] studied the effects of wet-bulb depression, timber thickness, and initial MC on the color of high-temperature-dried birch. The increased drying force increased the lightness and decreased the redness and the yellowness of wood; however, the difference in color between the surface layer and the interior of boards increased. They also found that an increase in thickness and initial MC accentuated the difference in color between the surface and the interior of boards and that pretreatment with water soaking decreased the difference in color between the surface layer and the interior of boards when low drying force was used, but this difference was increased when higher drying force was used [77]. Luostarinen [78] further determined that that the color of birch was correlated with microscopic characteristics of wood, such as cell types and their dimensions, and by drying processes. They found that in conventional drying, the most important factor causing darkened wood was wide latewood, while for vacuum drying it was thickness of the vessel walls, broad rays, and large amounts of axial parenchyma. Phenolics were abundant in ray parenchyma and tended to darken at elevated temperatures, less in conventional drying than in vacuum drying [78]. In two other studies, the discoloration of the surfaces of European white birch during vacuum drying was investigated, and it was determined that the yellowness of the surface layer was associated with the accumulation of low-molecular-weight phenolic extractives, and the redness with Brauns' lignin and possibly proanthocyanidins [79, 80]. For vacuum drying of oak (*Quercus spp.*), the lack of oxygen during drying was stated to improve lightness in color; however, temperature could affect the antioxidant potency [81].

Asghar et al. [82] investigated the surface color change of compression wood in spruce (*Picea abies* L.) and tension wood in poplar (*Populus nigra* L.) The color change of compression wood was found to be more remarkable than that of tension wood. Overall, the difference in the colorimetric parameters between the reaction woods and their corresponding normal woods was less significant after drying [82]. Nemeth et al. [83] investigated the color change of Robinia (*Robinia pseudoacacia*) and hybrid poplars during drying when temperatures from 20 to 80 °C and relative humidity from 95 to 20 % were used. The color of Robinia was shown to be more sensitive to heat than the poplars; poplars actually became brighter with drying at all temperatures [83].

A number of studies focused on color variation of tropical species due to drying. One experiment showed that lightness and yellowness are prevalent in the heartwood and sapwood of plantation *Vochysia guatemalensis*, and that visually perceptible changes occur in color during drying and under different drying conditions. For example, only lightness increased significantly after drying in heartwood, while all other parameters decreased and color differences between sapwood and heartwood decreased after drying. Different drying conditions accentuate differences in color between green and dried wood [84]. In another study, the color of marupá (*Simarouba amara*) was characterized, with focus on the effects of drying (kiln- and air-dried) and sawing direction (tangential and radial). Marupá is a grayish-white species, due mostly to its position on the yellow-blue axis (b*). Regardless of the drying method considered, the tangential direction presents a lighter color than the radially-sawn wood and air-drying produced wood with a lighter color [85].

The influence of storage conditions before kiln-drying on color was the subject of two research efforts. Stenudd [86] determined that log storage for 13 weeks under low-temperature conditions had no visible effect on the color of non-steamed sawn beech. He concluded that the reddish discoloration was mainly temperature-related, while the grayish discoloration was mainly controlled by the equilibrium MC (EMC) during the initial drying. Within the investigated climate interval, it was determined that EMC was twice as important as temperature for the final color [86]. In a similar effort involving conventional and vacuum drying, Katri and Mottonen [87] determined that different periods of log storage affected the synthesis of soluble proanthocyanidins during conventional drying and that the concentration of proanthocyanidins also correlated with changes in the color of birch wood. Discoloration appeared differently in conventionally dried and vacuum-dried wood, which indicates that the discoloration mechanism in these drying methods may differ chemically, and/or the compounds that take part in discoloration may be different at different drying temperatures [87].

Lumber Pre-sorting

Several approaches to sorting lumber before drying have been suggested over the years to avoid problems such as under- or over-drying, dimensional stability, and low-grade recovery. More recent work in this area includes pre-sorting based on MC and drying schedule modification as means to improve drying times and recovery [88]. Elustondo et al. [89] sorted hem-fir lumber prior to drying into three groups by electric capacitance and weight. They were able to reduce the drying time by approximately 10 % and over-dried lumber to practically zero [89]. Elustondo et al. [90] further demonstrated improvements in drying by sorting using the scaledry/sort/re-dry (Q-Sift®) strategy for drying of 2 by 4 Pacific Coast hemlock (*Tsuga heterophylla*) lumber. When using combined conventional and radio frequency vacuum drying technologies, the Q-Sift strategy reduced drying time by 4.6 %, increased lumber grade quality (4.7 % reduction in degrade), and reduced the planed lumber area [90]. It was estimated that by using a pre-sorting system that \$1.2 and \$2.8/m^3 could be gained in sales value. Elustondo et al. [91] went on to develop a method of sorting the entire lumber population into three sorts and then combining the sorted lumber into six subgroups. Laboratory and industrial tests on hem-fir lumber demonstrated that sorting into three lumber groups can potentially reduce drying time by 1 day approximately and increase lumber value in approximately \$8 USD per thousand board feet [91]. Another multi-variable pre-sorting approach was used by Sugimori et al. [92], who used cluster analysis in an attempt to pre-sort sugi (*Cryptomeria japonica*) lumber to minimize final MC variation. Their results indicated that while green lumber should be sorted by MC, it should first be sorted based on red and non-red heartwood colors; then non-red heartwood should be sorted by heartwood ration [92]. Berberović and Milota [93] studied how drying rate of lumber within Western hemlock (*Tsuga heterophylla*) logs are impacted as basic density, initial MC, heartwood percentage, and growth ring angle change based on location from the parent log and determined that sorting based on these variables should reduce drying time and greatly reduce final MC variability [93].

Pre-treatment to Accelerate Drying

Recent work on pre-treatment of lumber to accelerate drying include the use of "green kerfing," steaming, ultrasound pre-treatment, microwave pre-treatment, and compression. Green kerfing is a technique where thin slots (3 mm or narrower) are cut on the wide faces of dimension lumber, perpendicular to the grain [94]. It is claimed that kerfing accelerates drying by increasing the moisture loss through the end-grain (much faster than moisture loss in the tangential or radial direction of wood), and reducing warp during drying, all this with minimum loss of strength. The steaming of wood to reduce permeability has been shown to increase the drying rate and reduce defects in rubberwood (*Hevea brasiliensis*) [95]. Ultrasound pretreatment prior to vacuum drying has been shown to enhance the effective water diffusivity; where the higher the ultrasound power level, the longer the pretreatment time, and the lower the absolute pressure, the shorter is the drying time [96]. The increased mass transference rate and effective water diffusivity are attributed to changes in wood microstructure and removal of extractives [97]. Pre-treatment by compression to reduce the MC in wood in a short time period was shown to be effective for Poplar (*Populus tomentosa*) and Chinese fir (*Cunninghamia lanceolata*) [98].

Microwave pretreatments have been used to reduce the number and depth checks and honeycomb in the conventional kiln drying of backsawn/flatsawn messmate stringybark (*Eucalyptus obliqua*) [99] and to increase the diffusion coefficient of hinoki (*Chamaecyparis obtusa*) timber up to 3 % [100]. A pre-treatment with dielectric heating at radio frequency (RF) on sub-alpine fir results in higher permeability and increased drying rates both above and below the fiber saturation point, 18–30 % and 21–55 %, respectively [101]. The use of high temperature and low humidity as a pre-treatment to radio frequency vacuum (RFV) drying of boxed heart Japanese cedar (*Cryptomeria japonica*) timber resulted in a reduction of MC up to 25 % and a reduction in drying times from green to 15 % MC [102].

Effect of Drying on Wood Properties

The use of high temperatures in the drying process is known to degrade wood, leading to weight and strength losses. These losses depend on factors that include MC, heating medium, temperature, exposure period, and to some extent, species and size of the pieces involved [1]. Borrega and Karenlampi [103] studied the mechanisms that affect the mechanical properties of spruce dried at high temperatures and determined that thermal degradation of cell wall components and formation of irreversible hydrogen bonds influenced both the hygroscopicity and the mechanical properties of dried wood. Significant mass loss, caused by thermal degradation of cell wall components, occurs in slow high-temperature drying processes. Hornification influences strength and stiffness more than mass loss. Ductility was negatively affected by the mass loss and the hornification, the inelastic ductility being more sensitive than the elastic one. Microscopic cell wall damage caused by incompatibility of drying shrinkage did not affect the mechanical properties of macroscopic wood specimens [103]. When examining the effects of high-temperature drying on the cell wall porosity, it was suggested that high-temperature drying seemed to close large-diameter cavities in early wood cells, which was explained by irreversible hydrogen bonding in Norway spruce [104].

Oltean et al. [105•] offered an excellent review of work done on the effects of drying temperature on cracks and mechanical properties of wood. Among other conclusions, the authors stated that higher temperatures were associated with strength loss and increased brittleness, potentially due to depolymerization of hemicellulose and reduced hygroscopicity. Also, drying temperature had a greater effect on modulus of rupture than on modulus of elasticity. The authors noted that little research existed on the simultaneous effect of temperature on mechanical properties and occurrence of cracks, and that a disproportionate amount of literature deals with high temperature drying and very little with conventional temperature drying [105•].

Resistance to Mold and Biodegradation

Mold growth on lumber has become an increasing concern over the last decade due to concerns over mold spores and their impact on human health. While drying reduces the MC of lumber to support mold growth, there are some concerns about how drying may affect mold growth after drying. Also, drying methods can influence mold growth. For example, during the drying process for Norway spruce and Scots pine sapwood boards, it is possible to direct the migration of nutrients in sapwood toward one chosen side of each board by double stacking; the opposite side leaches out, which has a great impact on surface mold growth. Chemical analyses of monosaccharide sugar gradients beneath the boards' surfaces confirmed these results [106]. Others have noted a clear difference in discoloring mold fungus between wood dried at room temperature and kiln-dried wood [107].

Sehlstedt-Persson and Wamming looked the effect of the duration of high temperatures used in drying when the wood is at high MC and determined that these factors have a critical impact on the decay resistance of the heartwood of Scots pine. They also determined that steam conditioning after drying decreased durability in sapwood of Scots pine [108].

Environmental Issues of Drying Lumber

Concerns for environmental degradation and resource depletion have motivated industries to implement initiatives to reduce their impact on the environment, from waste reduction to the implementation of energy-saving equipment. Science has demonstrated abundantly that wood products require less energy to manufacture than alternative materials (e.g., steel, concrete), and that wood products have a negative balance of carbon (i.e., they store carbon). However, manufacturing of wood products has some environmental impacts, and much of this impact occurs during drying, mostly due to the high energy needs, the emission of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). These issues have been the subject of numerous research efforts, which are discussed in this section.

Life cycle assessment (LCA) has become the standard science-based method to evaluate the environmental impacts of products, from extraction of raw materials to disposal. LCA is based on the accounting of energy and materials associated with transformation processes. A number of studies on the environmental impacts of wood-based products using LCA were performed under the Consortium for Research on Renewable Industrial Materials project [109], including LCA on hardwood and softwood lumber manufacturing. The results from these studies confirm that drying represents a large part of the environmental costs associated with lumber manufacturing, including energy inputs, and volatile organic compounds (VOCs). In hardwood lumber manufacturing, for example, drying generates 1.2 kg/m^3 VOCs and consumes 70 to 80 % of the total energy [110]. For softwood lumber, CORRIM researchers found that drying consumes most of the fuel and VOCs emission amounted to 0.652 kg/m^3 [111].

The release of volatile organic compounds (VOCs) and total organic compounds (TCOs) during the dehumidification-drying of air-dried hardwood lumber was investigated by Beakler et al. (2005), by analyzing the effluent from a dehumidification kiln. Of the 13 hardwood species dried in 6 kiln charges, the largest amounts of TOCs were released by a mixed charge of white and red oak (*Quercus alba* and *Quercus rubra*, respectively) [112]. A similar experiment focused on conventional kiln-drying of green red and white oak, where red oak released the largest amount of VOCs, 0.154 to 0.358 lb per thousand board feet (MBF), while white oak released 0.058 to 0.227 lb per MBF; the authors suggested this difference may be related to the higher concentrations of acetic acid and acetaldehyde in red oak and presence of tyloses in white oak, which may limit the release of VOCs. In both species, most of the VOCs release occurred before fiber saturation point [113]. Lumber samples from a single loblolly pine log (*Pinus taeda*) were dried to measure emissions of terpenes, major chemical components in the VOC emissions of this species. VOCs from heartwood were 90 % larger than those from sapwood (on a pounds per dry ton as carbon), and 50 to 60 % of terpenes remained in the lumber after the drying process [114].

Dahlen et al. (2011) determined that when drying southern pine from green to 19 and 8 % MC, higher temperature schedules resulted in the largest emissions of hazardous air pollutants (HAPs, e.g., methanol, phenol, formaldehyde, acetaidehyde, propionaldehyde, and acrolein) and VOCs. The authors concluded that a southern pine mill would become a major source of HAPs (10 t of a single HAP or 25 t of total HAPs per year) when drying more than 53 to 67 million board feet of lumber (MMBF) (or 106 to 124 m^3) to 8 % MC. As for VOCs, relatively larger emissions were measured for material with larger presence of knots and higher temperatures [115]. HAPs emissions during the drying of five softwood species and one hardwood (red alder, *Alder rubra*) were measured under the National Council for Air and Stream Improvement (NCASI) Method 105. Species included ponderosa pine (*Pinus ponderosa*), white wood (mix of western pines, fir, and spruce), Douglas-fir (*Pseudotsuga menzeisii*), western hemlock (*Tsuga heterophylla*), white spruce (*Picea glauca*), and red alder (*Alnus rubra*). Two drying schedules were used, one "conventional" and another with high temperature; and a target MC was 15 % was used. Results revealed a strong association between temperature and emissions of methanol and formaldehyde. Red alder exhibited the largest amounts of HAPs, which was attributed to the large number of methoxyl groups in hardwood lignin and the higher hemicellulose content and number of acetyl groups [116].

The removal of moisture from wood is one of the most energy-intensive processes in the manufacturing of wood products. Investigations into the energy used in drying and its reduction have focused on comparing the energy used between drying methods and modeling energy use. TBi-Guang et al. [117] compared the energy consumption between conventional, dehumidification, and combined conventional-dehumidification drying methods. They found that dehumidification drying used the least energy but had the longest drying time. Energy consumption for the combined drying method was 18 % more than that in the dehumidification drying but 21.5 % less than that in the conventional drying, and the drying time is half of that in the dehumidification drying [117]. When comparing the energy requirements between conventional, all electrical and hybrid kiln drying, reductions in total (electrical and fossil) energy consumption for the all-electrical and hybrid drying cycles ranged between 42 and 48 % compared with the total energy consumption for conventional drying [118].

The energy consumption used in kiln-drying was modeled by Elustondo and Oliveira [119] where their model used an empirical equation that is calibrated with experimental data consisting of lumber initial and final MC and total drying time. The model also assumed that diffusion controls the drying process for the total moisture range, not only below fiber saturation point, as the theory indicates and was demonstrated to accurately reflect energy used in three trial runs [119].

Summary and Conclusions

While the methods to dry wood have not significantly changed over the last decade, there have been many advances in improving the technology and understanding the process. The modification or addition of technology to current methods has allowed for the more rapid drying and attainment of better quality for specific species and thicknesses of materials. Efforts to develop new methods to control the drying process to further reduce drying times and improve quality continue. The increasing use of lesser-known species has also motivated development of drying schedules to achieve specific quality requirements. We also have a much better understanding of the energy use and environmental impact of wood drying.

Based on the trajectory of the research published over the last decade and the current needs of commercial drying operations, we predict that future research on wood drying will focus on two thematic areas: (1) a focus on improving the quality of wood dried and reducing the time required to dry the material and (2) a focus on reducing the energy requirements and environmental impact of wood drying. These two thematic areas are related, as the first will lead to improvements in the second. Also, we believe that the first thematic area can be further subdivided into (a) research on vacuum drying applied to higher moisture content material, its application to different species, and increasing its efficiency with current species and thicknesses of material; (b) research on the control of the drying process of conventional, high temperature, and vacuum drying technologies; (c) research on the development of new schedules for each of the technologies mentioned previously for tropical and hybrid species. Each of these thematic areas is related, as each will ultimately improve the quality, reduce drying time, and reduce the energy used for wood drying.

Compliance with Ethical Standards

Conflict of Interest Drs Bond and Espinoza have no conflicts of interests to declare.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by the author.

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