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Drying Right: A Study of Global Wood Seasoning Methods by Species with Recommendations for Nepal's Forest Products Sector

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ABSTRACT

Wood seasoning is a critical step in timber processing that directly affects the durability, strength, and dimensional stability of wood products. This study reviews global wood seasoning practices, focusing on how methods vary based on species-specific properties such as density, fiber structure, moisture content and shrinkage rates. Common techniques like air drying, kiln drying, and advanced methods (vacuum, steam, hybrid) are compared for their effectiveness across both hardwood and softwood species. The research highlights the importance of matching drying strategies to wood characteristics to minimize defects such as warping, cracking, and fungal attack or decay. Drawing from international best practices, the study offers practical recommendations for Nepal's forest product sector, where diverse species and climatic conditions require locally adapted solutions. Species such as *Shorea robusta* (Sal), *Dalbergia sissoo* (Sissoo), and *Alnus nepalensis* (Uttis) are considered for their seasoning challenges. The study suggests promoting low-cost solar kilns and developing species-specific drying schedules. Additionally, strengthening technical capacity to improve timber quality, reduce post-harvest loss, and support a more sustainable, climate-resilient wood industry in Nepal.

Keywords: wood seasoning, kiln drying, air drying, timber moisture content, species-specific drying, wood processing

1. INTRODUCTION

Timber has long been valued as a fundamental material in human civilization, used for heating, cooking, weapons, building homes and tents, crafting vehicles and in artistic endeavors owing to its versatility, sustainability and aesthetic appeal (Batjargal *et al.*, 2023; Brischke, 2019; Ganem Karlen, 2022; Hwang *et al.*, 2022). Today, timber remains a primary construction material, with nearly one-third of globally harvested wood used in building applications (Hildebrandt *et al.*, 2017; Lyons, 2006; Park *et al.*, 2024; Ramage *et al.*, 2017). Its use also contributes to sustainable development by reducing carbon footprints and supporting climate-friendly construction (Akpan *et al.*, 2021; Kaufmann *et al.*, 2011; Roos *et al.*, 2023). However, despite its environmental and structural advantages, timber is vulnerable to various forms of deterioration depending on its expo-

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sure, ranging from indoor humidity to outdoor conditions like rain, UV radiation, and ground contact (Adhikari and Ozarska, 2018; Reinprecht, 2016). Both abiotic factors, such as temperature fluctuations and moisture, and biotic threats like fungi, molds, and insects, can compromise the physical and chemical integrity of wood, shortening its lifespan and reducing its competitiveness compared to other construction materials (Erdenebileg *et al.*, 2020; Hill, 2006; Marais *et al.*, 2022). To enhance the performance and longevity of wood, seasoning, the process of controlled drying is considered one of the most effective treatments (Areo *et al.*, 2023; Chauhan, 2022; Kim *et al.*, 2023). Seasoning reduces the moisture content of green wood below the fiber saturation point (typically < 22%), thereby minimizing shrinkage, warping, fungal decay, and structural weaknesses (Chauhan, 2025; Desch and Dinwoodie, 1996; Olorunnisola, 2018). Properly seasoned timber is more stable, lighter, and mechanically stronger, making it suitable for structural and aesthetic applications alike (Kollmann, 1968; Okwori, 2014; Shirmohammadi *et al.*, 2021). Seasoning also brings economic benefits by lowering transportation costs and increasing wood's dimensional (Järvinen *et al.*, 2022; Sfeir *et al.*, 2021; Sumardi *et al.*, 2024).

However, the effectiveness of seasoning varies depending on several factors, especially wood species, which differ in density, moisture content, fiber structure, and shrinkage characteristics (Koch *et al.*, 2015; Ruffinatto *et al.*, 2023). Hardwoods such as *Eucalyptus* spp., *Oak* (*Quercus* spp.), and *Teak* (*Tectona grandis*) are difficult to season due to high shrinkage and low moisture diffusivity (Dawson *et al.*, 2020; Gonya *et al.*, 2022; Simpson, 1991), whereas softwoods such as Pine (*Pinus* spp.), Spruce (*Picea* spp.), and Fir (*Abies* spp.) are generally easier to dry due to their uniform cell structures and lower densities (Grønli *et al.*, 2002; Kaba *et al.*, 2023; Siau, 1984). Research indicates that high-temperature drying of hardwoods, such as beech (*Fagus sylvatica* L.), markedly reduces hemicellulose content. While this may enhance the wood's dimensional stability, it can also increase risks of defects such as warping, splits, and color variations (Klement and Huráková, 2016). Environmental conditions (temperature, relative humidity, and airflow) also play a key role in the drying process, with the ideal moisture content for most uses ranging between 12%–20% (Alam *et al.*, 2022; Rathnayake and Amarasekera, 2013). Research showed that an increase in drying temperature decreases the moisture content, leading to warping, cracking and reduction in the mechanical properties of wood (Espinoza and Bond, 2016; Nakagawa *et al.*, 2020). Further studies confirm that specific temperature ranges can optimize moisture removal without adversely affecting wood properties (Arabi and Ghalehno, 2022; Chai *et al.*, 2018).

Wood seasoning requires species-specific approaches due to the unique anatomical and physical properties of different timber types. Mujumdar and Law (2010) recommend high-temperature kiln drying at 110℃–120℃ with initial steam conditioning for 15–30 minutes at 100℃ to stabilize the resin in pine. Another important species, Spruce (*Picea* spp.), tends to develop spiral grain distortion during drying; therefore needs moderate temperature kiln drying at 80℃–90℃ with weight stacking to prevent warping (Patel and Bade, 2023; Sandberg *et al.*, 2021). Douglas fir (*Pseudotsuga menziesii*), known for its susceptibility to internal checking in thick dimensions, benefits from a low-temperature pre-drying phase at 40℃ for 30 days before final kilning (Boone, 1988). Oak (*Quercus* spp.), particularly vulnerable to shrinkage and honeycombing, demands careful treatment. White oak responds best to a 60-day air drying period followed by kiln drying at 60℃ with 85% relative humidity, while red oak can tolerate a slightly faster schedule at 65℃ with frequent conditioning cycles (Elustondo *et al.*, 2023; Pandey and Pant, 2023; Yang *et al.*, 2022). High-value tropical hardwoods such as Teak (*Tectona grandis*), Meranti (*Shorea* spp.), Keruing (*Dipterocarpus* spp.), and Gmelina (*Gmelina arborea*) that are widely harvested across countries like Indonesia, Thailand, Vietnam, and the Philippines have high initial moisture content and dense fiber structures, making them susceptible to drying defects such as checking, collapse, and honeycombing when exposed to rapid drying conditions (Phonetip *et al.*, 2019a; Salas and Moya, 2014). In Nepal, traditional air drying remains common, especially in community-managed forests, with limited kiln infrastructure and technical expertise. Local species such as *Sal*, *Uttis* (*Alnus nepalensis*), and *Sissoo* are often dried without proper moisture monitoring, leading to high post-harvest losses (Pandey *et al.*, 2024; Paudel and Karki, 2024). However, recent initiatives by forestry institutions and universities are promoting solar kiln use and encouraging research on species-wise drying behavior to support small-scale enterprises. Research institutions like the Forest Research Institute (FRI) in Dehradun, India have developed species-specific drying schedules, particularly for tropical hardwoods prone to warping and cracking (Indian Council of Forestry Research & Education [ICFRE], 2013). Likewise, China has made significant advancements in high-tech kiln systems, vacuum drying, and computer-controlled drying chambers, particularly for commercial species like Chinese fir (*Cunninghamia lanceolata*) and Poplar (*Populus* spp.). These technologies are supported by state investment and aligned with China's focus on value-added wood processing and export quality (Yu *et al.*, 2025).

In Nepal, where timber demand is rising in both the construction and furniture sectors, the lack of species-specific drying protocols, along with geographic and climatic variability, poses significant challenges. Improper seasoning leads to high post-harvest losses and reduced wood quality, especially for valuable native species like *Shorea robusta* (Sal), *Dalbergia sissoo* (Sissoo), and *Alnus nepalensis* (Uttis). In this context, developing climate-adapted, species-sensitive seasoning strategies is critical for sustainable timber utilization. This study presents a comprehensive review of current global timber seasoning methods, examining their effectiveness, species-wise suitability, and associated challenges. Drawing from peer-reviewed literature accessed via Google Scholar, SpringerLink, and ResearchGate, the study evaluates the performance of various techniques across different timber species. It further aims to provide practical recommendations for Nepal's forest product sector, emphasizing efficient, low-cost, and locally adaptable methods to enhance wood quality and reduce processing losses.

2. METHODS

2.1. General

We used the standard method called PRISMA for systematic literature review, which includes resource eligibility, exclusion criteria, data abstraction, and analysis. The review was based on a systematic search of articles from electronic databases: Google Scholar, Springer Link and Research Gate. We choose these databases as they cover about 613 disciplines with minor disciplines (wood science and technology, timber, forestry, forestry management, Manufacturing, machines, tools, processes). A manual search was also performed, in which 25 articles were imported. The advanced search tool in databases was used for a rigorous search on assigned topics (Table 1). All the searched articles were imported into Mendeley reference management software, and duplicates were deleted.

2.2. Inclusion and exclusion criteria

All articles were gathered through search engines and compiled. Only peer-reviewed papers were selected for inclusion. These articles are specially focused on the different seasoning techniques or methods applied to various timber species, showing different properties and results. Both printed and online journals, which were

Table 1. Keywords and number of articles retrieved from different databases

Keywords search	Google Scholar	SpringerLink	ResearchGate
(“Wood seasoning” OR “timber seasoning” OR “timber drying”) AND (“techniques” OR “drying”) AND (“different wood species” OR "timber")	108	59	39
(“Wood seasoning” OR “timber seasoning” OR “timber drying”) AND (“drying” OR “methods”) AND (“different wood species” OR “Timber”) NOT (“softwood” OR “hardwood”)	77	154	40
(“different seasoning techniques” OR “drying methods”) AND (“wood drying” OR “seasoning”) AND (“different timber”)	41	52	43
Manual search (30)			
Total	226	265	122

listed on their respective journal websites, were selected for the study. Non-peer-reviewed articles such as news articles, case studies, conference papers, chapters, reports and articles in predatory journals were excluded. To ensure a focused and organized review, we only selected the articles published in English between January 1st, 2015 and December 31st, 2024. While studies unrelated to seasoning parameters were excluded. The overall inclusion and exclusion criteria are shown in Table 2.

2.3. Data extraction

The searched articles were imported into Mendeley reference management software (Mendeley desktop version 1.19.5). A total of 613 articles were initially identified from databases: 226 from Google Scholar, 265 from SpringerLink, and 122 from ResearchGate (Fig. 1). Additionally, 30 articles were found through manual searching, bringing the total to 643. After removing 227 duplicate entries, 416 articles remained. Following title screening and selection of peer-reviewed journal articles, 70 articles were identified as eligible for the second phase screening. These articles were then further assessed by reviewing their abstracts, and those meeting the inclusion criteria were selected for full-text review. Ultimately, 25 research studies were included in the final data analysis. The review process was conducted in accordance with PRISMA guidelines (Moher *et al.*, 2010).

We use a data extraction form for gathering information from every publication, including the study’s methodology, goal, drying time and conditions of wood. Reviews of the publication's title, abstract, and entire content were completed separately. Team members care-

Table 2. The inclusion and exclusion criteria

Criterion	Eligibility	Exclusion
Literature type	Research articles (journal)	Review journal articles, book, chapter, book series, conference article, report, case studies, comparative analysis
Language	English	Non-English
Timeline	Between 2015 and 2024 Full length article peer-reviewed journal	< 2014 Published abstract

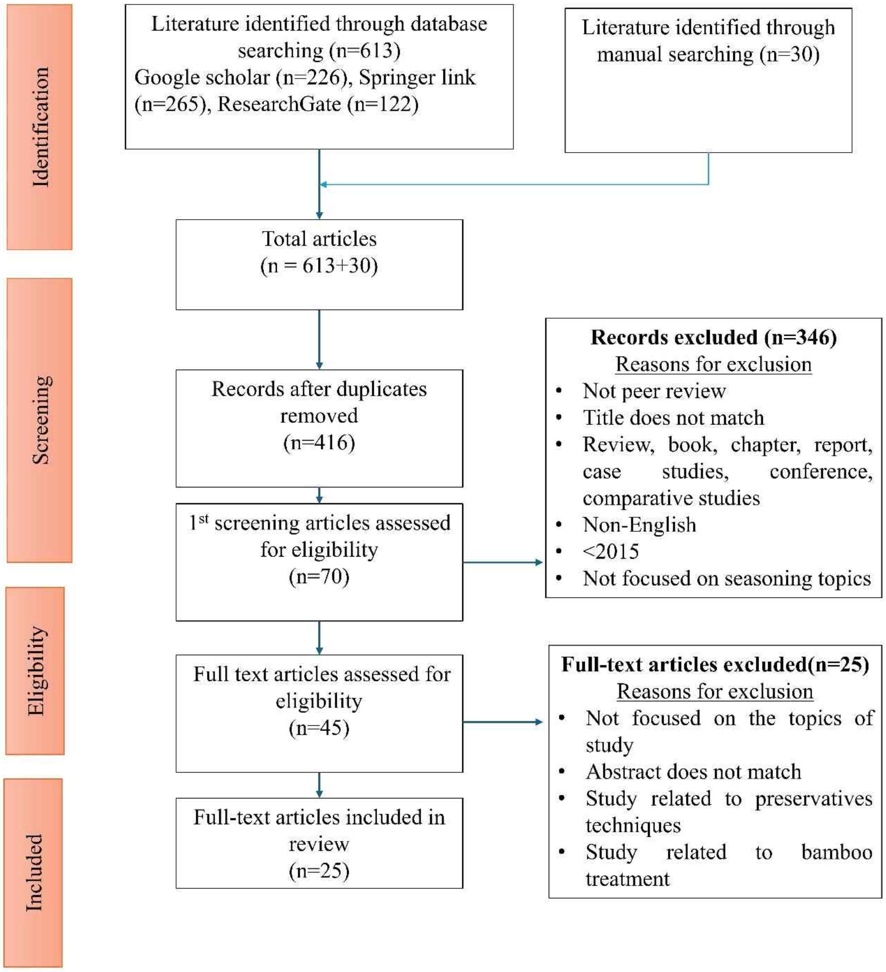

Fig. 1. PRISMA flow diagram representing the study's systematic review and selection process.

fully screened the abstract, the study's location, and the methods employed in accordance with the eligibility requirements and exclusions. When more information was needed, we also got in touch with the authors. Consent was used to settle disagreements on the eligibility of any articles.

3. RESULTS

The review included 25 articles, with the distribution of publication years as follows: three articles each were published in 2015, 2017, 2018, 2020, and 2023; two articles in 2021; and one article each in 2019 and 2022 (Fig. 2). The highest number of articles (six) was published in 2024. These articles originated from 15 different countries: China (n = 4), Australia (n = 4), Poland (n = 3), Nigeria (n = 2), Canada (n = 2; Fig. 3), and one article each from India, Pakistan, Bangladesh, Japan, New Zealand, Malaysia, Estonia, Spain, the Slovak Republic, and Central Africa. The studies applied various seasoning methods to different timber species, focusing on analyzing optimal drying conditions, moisture reduc-

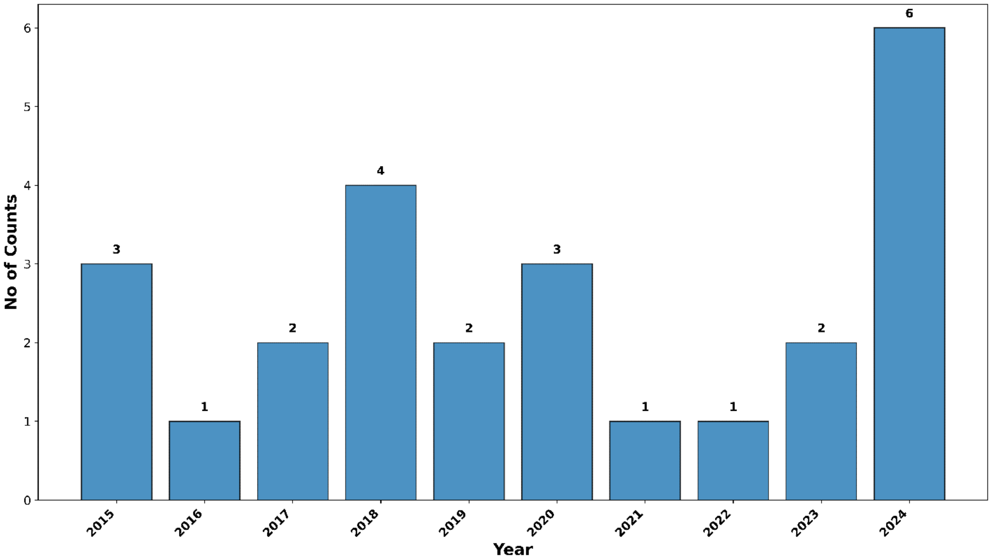

Fig. 2. Number of articles published in each year in the assigned topic.

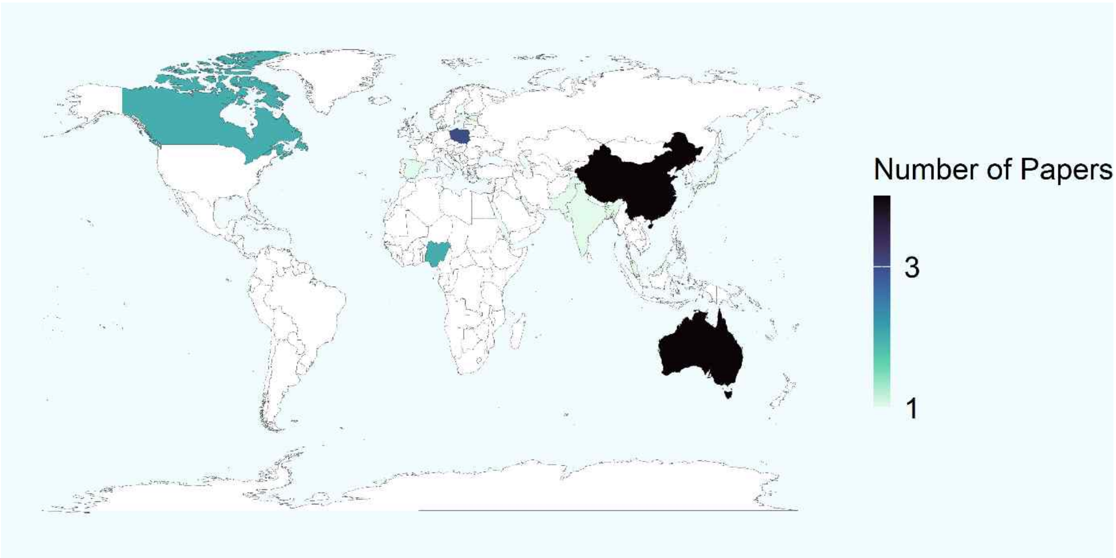

Fig. 3. Percentage of articles studied in each country.

tion, and seasoning defects, as summarized in Table 3. Various seasoning methods were explored across the reviewed studies, including kiln drying (n = 10), solar drying (n = 6), air drying (n = 4), vacuum drying (n = 3), oven drying (n = 2), steam drying (n = 2), microwave treatment (n = 1), and Natural drying (n = 1; Fig. 4).

Table 3. Publication identified in main databases (Google Scholar, SpringerLink and ResearchGate) through systematic review

Country	Timber species	Seasoning method	Drying time and conditions	Moisture reduction	Common defects	References
Pakistan	*Dalbergia sissoo* Roxb., *Acacia nilotica* Wild, *Pinus Wallichiana* A.B. Jacks	Oven-dried method	- Temperature: 60℃, 80℃ and 100℃ - Time: 10 and 15 d	Percentage weight loss *Pinus wallichiana* > *Acacia nilotica* > *Dalbergia sissoo*. Sapwoods > Heartwoods	No common defects mentioned, but mentioned negative effects related to drying defects.	Fatima *et al.* (2015)
Estonia	*Betula* spp. (Birch), *Populus* spp. (Aspen), *Alnus glutinosa* (L.) *Gaertn.* (Black alder)	Feutron climate chamber (Kiln)	- Time: 1, 12, 36, 60, 84, 108, 132 h. and surrounding - Temperature: 20℃, 47℃, 48℃, 50℃, 52℃ - Surrounding RH: 60%, 95%, 90%, 80%, 69%, 59%, 49%	Average MC after first drying phase: Black alder (55%), Aspen (62%), birch (64%), pine sapwood (60%), Final MC: Below 30%	Birch, aspen, black alder showed different deformation patterns to drying stresses.	Tamme *et al.* (2023)
Nigeria	*Alstonia boonei* (Ahun), *Ricinodendron heudelotii* (Erimando), *Guarea cedrata* (Olofun)	Solar kiln dryer and Air-drying shed	Solar kiln drying - Temperature: 31℃–48℃, with peaks up to 58℃. - Time: Several months to years - Air drying shed temperature: 24℃–31℃, with peaks up to 32℃. - Time: 1–4 wk	MC after 41 d - *Alstonia boonei:* 82.26%–6.46% - *Guarea cedrata:* 64.6%–9.55% - *Ricinodendron heudelotii*: 368.5%–8.97%	- Shrinkage was higher in the solar kiln than air drying shed. - No physical degradation.	Owoyemi *et al.* (2015)
Malaysia	*Acacia mangium* (acacia), *Hevea brasiliensis* (Rubberwood), *Azadirachta excelsa* (Sentan), *Neolamarckia cadamba* (kelempayan)	Air drying	- Temperature: 60℃, 80℃, 100℃, and 120℃ - RH: 78%, 80%, and 87%	MC - *Acacia mangium*: 97.8%–11.5% - *Hevea brasiliensis*: 52.7%–11.6% - *Azadirachta excelsa*: 42%–13.6% - *Neolamarckia cadamba*: 75.8%–14%	Acacia showed many internal cracks dried at 100℃.	Hermawan *et al.* (2020)

Table 3. Continued

Country	Timber species	Seasoning method	Drying time and conditions	Moisture reduction	Common defects	References
Spain	*Quercus pyrenaica* Willd	Natural seasoning Alternative seasoning	Natural seasoning - Temperature (14.4℃) and average precipitation (504 mm^3/yr). - Time: 2 yr Alternative seasoning - Time: 4 mon, same as natural and washed in unchlorinated water through immersions (7 immersions, 20 min each), air circulated for 10 d and dried at 50℃ for 24 h.	NA	Chemical and structural changes in *Quercus pyrenaica* Willd. Wood due to seasoning and toasting.	Martínez-Gil *et al.* (2020)
Australia	*Eucalyptus delegatensis*	Greenhouse solar drying	Daytime: Maximum temperature of 43℃, RH (72%), air velocity (1–2 m/s) Nighttime: Ambient temperature, RH (90%), air velocity (0.5–1 m/s)	MC (75%–12%)	Compressive and tensile strain, timber distortion, internal cracking and collapse	Phonetip *et al.* (2019b)
Japan	*Cryptomeria japonica* (Japanese cedar)	Low-vacuum medium temperature drying	Experiment 1: Drying over a total of 10 days at 80℃ for 12 h and 80℃–90°C, 40 kPa, 228 h Experiment 2: Steaming first 12 h, and the sample was heated to 80℃ under standard atmospheric pressure	Experiment 1: Average MC (100%–28.4%) Experiment 2: Average MC (100%–13.8)	Wrapping in experiment 2, timber was reduced.	Jiang *et al.* (2024)

Table 3. Continued

Country	Timber species	Seasoning method	Drying time and conditions	Moisture reduction	Common defects	References
Slovak Republic	Maple wood	Air-conditioned room Hot air dryer	Air-conditioned room: Air temperature (20℃) and RH (60%). Hot air dryer: Steam thickness 38 mm	MC (50%–10%)	An undesirable color change occurred due to improper drying	Dzurenda (2020)
Australia	*Eucalyptus macrorhyncha*	Microwave treatment followed by Kiln drying	Microwave system (60 kW) Air temperature: 20℃–150℃ Low-level microwave treatment (LMW; 145 s) High-level microwave treatment (HMW; 190 s). Kiln drying temperature: 40℃, 45℃, 50℃, 60℃	LMW MC (60%–10%) HMW MC (69%–12%)	LMW showed lower internal cracks and surface checks than the control	Balboni *et al.* (2018)
Nigeria	*Prosopsis. Africana* (Okpeye)	Mixed-mode solar kiln	- Temperature range: 38.8℃–61.71℃ - Time: 360 h	Kiln drying MC (66.27%–12.9%) Open-air-drying MC (66.27%–20.1%)	- Uniform drying with minimal defects in kiln-dried wood - Seventy per cent of wood warping and end checks in open-dried	Ugwu *et al.* (2015)
Poland	*Picea abies* K, (Spruce), *Fagus silvatica* L. (Beech)	Semi-industrial kiln	1st stage drying - Temperature: Rapid heating up to 80℃ - RH: 90%–100% 2nd phase drying - Temperature: Up to 105℃ - RH: 80%–90%	MC - Spruce (37.36%–10%) - Beech (80.32%–10%)	Strong relationship between wood temperature and the gradient of MC	Baranski (2018)
China	*Eucalyptus grandis*, *Eucalyptus urophylla*	Dryer kiln equipped with a vapor generator	- Steaming temperature: 80℃, 100℃, and 120℃. - Steaming duration: 4 h after pre-heating at atmospheric pressure	MC (120%–7%)	Decrease in defects, including edge bends, surface splits, and inner splits	Kong *et al.* (2018)

Table 3. Continued

Country	Timber species	Seasoning method	Drying time and conditions	Moisture reduction	Common defects	References
China	Poplar timbers	Solar drying	- Solar irradiation: 0–2,000 W/m² - Temperature: 40℃–120℃ - RH: 0%–100%	MC - Spring (71%–10%) - Summer (110%–11.6%) - Autumn (113%–11.1%) - Winter (73.9%–11.2%)	Wood dimensional changes during the drying process (summer > spring > winter > autumn)	Chi *et al.* (2024)
Australia	*Eucalyptus delegatensis*	Solar kiln with a conventional laboratory greenhouse-type kiln	Daytime conditions (07:30–17:30) - Temperature: 45℃ - RH: 60% - Air velocity: 1 m/s Nighttime conditions (17:30–07:30) - Temperature: 12℃–23℃ - RH: 80% - Air velocity: 1 m/s - Time: 87 d	MC (65%–12%)	- Surface cracking was detected in 9 days of drying - Internal cracking on days 28, 42, and 87 d - Cupping, spring, and bow observed	Phonetip *et al.* (2019a)
New Zealand	*Pinus radiata* D. Don and *Nothofagus menziesii*, *Nothofagus fusca* (Hook.f) Oerst.	Supercritical CO_2 followed by oven drying	- Dewatered time over six weeks - CO_2 pressure (between 4 MPa and −20 MPa supercritical) with 2 min each for pressurization	MC - *Pinus radiata:* 94%–30% - Dewatering efficiency: 94% - *Nothofagus fusca*: 32%–30% - Dewatering efficiency: 4%	- Sapwoods (no differences in shrinkage and checking between dewatered then oven dried) - Heartwood (higher checking)	Dawson and Pearson (2017)
Central Africa	*Triplochilon scleroxylon* (Obeche), *Chlorophora excelsa* (Iroko), *Entandrophragma cylindricum* (Sapele)	Solar drying	- Temperature: 65℃ at noon - Time: 21 d (November and December) - Drying air velocity: 1.5 m/s - Ambient room temperature: 23.7℃–28.1℃ - RH: 10%–100%	MC - *Triplochilon scleroxylon* (0.4–0.15 kg/kg) - *Chlorophora excelsa* (0.48–0.18 kg/kg) - *Entandrophragma cylindricum* (0.42–0.18 kg/kg)	Wood quality degradation	Simo-Tagne and Bennamoun (2018)

Table 3. Continued

Country	Timber species	Seasoning method	Drying time and conditions	Moisture reduction	Common defects	References
India	*Melia dubia*	Vacuum drying	- Low pressure level (200 mm Hg), melting point of the phase change material (PCM) - Temperature: 55℃, 60℃, 65℃, and 70℃. - Two cycles time: 112 and 162 min.	Cycle 1 MC loss: 1.28% Cycle 2 MC loss: 2.35%	No common drying defects observed	Shailendra (2024)
Australia	*Eucalyptus delegatensis*	Solar kiln	Daytime - Temperature: 43℃ - Time: 07:30–17:30 - RH: 72% - Air velocity: 1–2 m/s Nighttime - Ambient temperature - Time: 17:30–07:30 - RH: 90% - Air velocity: 0.5–1 m/s	MC (75%–12%)	Internal cracks are found inside wood, often invisible on the surface.	Phonetip *et al.* (2017)
Poland	*Pinus sylvestris* L.	Kiln drying	- Dry bulb temperatures: 30℃, 40℃ and 50℃ - Wet bulb depression: 45℃ and 6℃	Average MC (96%–13.73%)	Cracking and warping, higher dry bulb temperature increased the risk of cracking	Majka *et al.* (2024)
China	*Cryptomeria fortune* (Chinese cedar wood)	Conventional drying and superheated steam drying	Conventional drying (CON) - Dry bulb temperature: 55℃–75℃ - RH: 90%–34% - Time: Varies based on MC stages. Super-heated steam drying (SHS) - Temperature: 3℃–15℃ - RH: 90%–60% - Time: Faster than CON drying due to higher heat and mass transfer rates	MC (120%–140% to 9.81% for SHS and 10.26% for CON)	- Physical damage to the wood cell wall - Lower swelling in SHS and moderate swelling in CON - Swelling efficiency was higher in the volumetric dimension than radial and tangential dimensions in both methods	Bao and Zhou (2017)

Table 3. Continued

Country	Timber species	Seasoning method	Drying time and conditions	Moisture reduction	Common defects	References
Bangladesh	*Gmelina arborea* (Gamar), *Swietenia macrophylla* (Mahagony) and *Mangifera indica* (Mango)	Accelerated drying and Kiln drying	Accelerated drying - Dry bulb temperature (80℃–130℃) - Wet bulb temperature: 50℃–75℃ - Time: 96 h - RH: 45%–83% Drying *Gmelina arborea* (Gamar) - Temperature: 45℃–82℃ - RH: 35%–90% - Time: 14 d *Swietenia macrophylla* (Mahogany) - Temperature: 35℃–80℃ - RH: 56%–80% - Time: 11 d *Mangifera indica* (Mango) - Temperature: 40℃–83℃ - RH: 65%–85% - Time: 10 d	MC - *Gmelina arborea* (Gamar; 91%–12%) - *Swietenia macrophylla* (Mahogany; 84%–12%) - *Mangifera indica* (Mango; 84%–12%)	- Accelerated drying schedule caused defects like checking, splitting, and cupping. - No drying defects - Higher MOE and MOR in seasoned wood	Alam *et al.* (2022)
Canada	*Tsuga heterophylla*	Klin drying	- Temperature: 48.9℃, 57.8℃, 54.4℃, 60℃, 62.2℃, 71.1℃ and 78.8℃ - Time: 12 h and 24 h - RH: 100%, 83.3%, 62.7%, 46.1%, 41%, 37%, 30%, 79.4%, 65%	- Shell MC (25.5%–6.0%) - Core MC (25.5%–6.8%)	Did not mention drying defects, but a significant core-to-shell moisture gradient was observed.	Rahimi *et al.* (2024)

Table 3. Continued

Country	Timber species	Seasoning method	Drying time and conditions	Moisture reduction	Common defects	References
China	*Eucalyptus urophylla*	Air drying, kiln drying, microwave vacuum drying	Air drying (AD) - Temperature: 23.7℃ - RH: 68.4% Kiln drying (KD) - Temperature: 65℃–75℃ - Time: 100 h Microwave vacuum drying (MVD) - Temperature: 40℃–45℃ - Voltage: 220 kV - Vacuum degree: 0.05–0.06 MPa - Microwave power: 800 W	Air drying - MC (84%–15.5%) Kiln drying - MC (final moisture 12%) MVD (25.0%–14.3%)	MVD and KD cause macro cracks, and AD drying causes tylose formation	Lu *et al.* (2024)
Poland	*Pinus sylvestris* L	Kiln dryer	Dry-bulb temperatures: 55℃, 60℃, and 65℃	Final MC (6%–8%)	Drying defects and final MC are influenced by initial MC and wood density	Majka *et al.* (2024)
Canada	*Tsuga heterophylla [Raf.] Sarg.* (Western hemlock), (*Abies amabilis* [*Dougl.*] *Forbes*) Amabilis fir	Kiln drying (conventional heat-vent research kiln)	Six-step drying combining time and moisture-based steps: 15.5℃ (6 h), 30℃ (12 h), 45℃ (18 h), 60℃ (24 h), 67.5℃ (30 h), 90℃ (36 h)	- Drying step 1 & 2: Target MC 21% - Steps 3 & 4: Target MC 16% - Steps 5 & 6: Target MC 11%	Variations in MC on several drying methods, while density had the least significant	Rahimi *et al.* (2022)

MC: moisture content, RH: relative humidity.

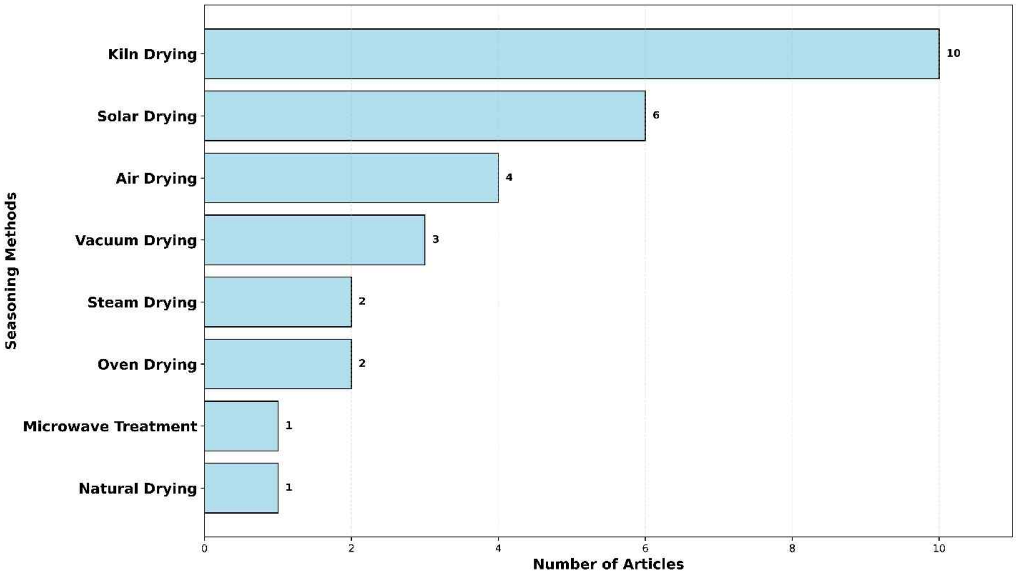

Fig. 4. Seasoning methods considered in the study, with the number of articles on assigned topics.

4. DISCUSSION

In the present review, most studies on wood drying and seasoning originate from countries such as India, China and Bangladesh. These countries appear more frequently not because of any pre-selection, but because they are active research hubs with well-established forestry and timber industries. Their substantial research output reflects both the scale of their forest resources and the economic significance of wood utilization in construction, furniture manufacturing, and related industries. Although some countries (e.g., Canada, Poland, and Estonia) represent temperate climatic zones that differ from Nepal, their research remains relevant as it contributes to understanding fundamental drying mechanisms, defect control, and energy-efficient technologies that are universally applicable. In contrast, studies from India, Bangladesh, and parts of Africa are particularly valuable for Nepal because they share similar tropical and subtropical climates, species compositions, and small to medium-scale wood industries. Therefore, even though Nepal currently has limited published research in this field, insights drawn from neighboring and global contexts can be adapted to its local conditions. By integrating findings from countries with comparable climates and species, while incorporating technological advancements from temperate regions, this review seeks to provide a balanced and applicable knowledge base for improving wood-drying practices in Nepal.

Studies showed that various methods are employed under both natural and artificial conditions, with drying parameters such as time, temperature, and initial moisture content varying accordingly. Due to differences in environmental and climatic conditions, many wood species require specific seasoning approaches tailored to their regional growth characteristics. Although seasoning can lead to certain defects, such as internal cracks or warping, some wood species undergo the process without showing any noticeable defects. Understanding these variations is essential for optimizing seasoning methods to ensure high wood quality and minimize processing losses.

4.1. Influence of drying methods and conditions

Kiln drying and solar kiln drying are among the most widely used artificial seasoning methods globally, especially in countries like Nigeria, Australia, China, Poland, and Canada (Kong *et al.*, 2018; Owoyemi *et al.*, 2015; Majka *et al.*, 2024; Phonetip *et al.*, 2019b; Rahimi *et al.*, 2024). These techniques have consistently demonstrated significant reductions in drying time while maintaining control over environmental variables such as temperature and humidity (Augustina *et al.*, 2023; Elwakeel *et al.*, 2025; Nawawi *et al.*, 2023; Tang *et al.*, 2025). For instance, in Nigeria, *Pericopsis africana* was successfully kiln-dried in just 15 days, a dramatic improvement compared to several months required under open-air drying conditions (Ugwu *et al.*, 2015). The controlled environment in kiln systems ensures uniform drying and minimizes moisture content variability in the final product, thus improving dimensional stability and reducing defects like warping and checking (Dashti *et al.*, 2012; Majka *et al.*, 2024; Ross, 2021; Xiang *et al.*, 2012).

Solar kiln drying, while significantly less energy-intensive, is generally slower and more sensitive to local climatic conditions. In Central Africa, for example, rapid moisture loss under low humidity conditions during solar drying led to severe wood degradation, such as surface checks and case hardening. This underscores the importance of environmental control even in low-tech solar systems (Lee *et al.*, 2024; Simo-Tagne and Bennamoun, 2018). Despite this, solar drying remains a viable option in regions with abundant sunlight and limited access to electricity, especially when combined with basic airflow regulation and shading techniques (Apriandi *et al.*, 2024; Helwa *et al.*, 2004). Vacuum and microwave-assisted drying methods have shown significant promise in advanced timber processing sectors, particularly in countries such as India, Australia, China, and New Zealand. These techniques are especially effective for hardwood species with high initial moisture content (MC), offering faster drying cycles and reduced seasoning defects compared to conventional methods (Lu *et al.*, 2024; Shailendra, 2024). Vacuum drying accelerates the removal of moisture by lowering the boiling point of water, which enhances internal moisture migration with minimal thermal degradation. Studies from Australia demonstrated that vacuum-dried Eucalyptus species achieved optimal MC in shorter timeframes while reducing internal checks and collapse (Bond and Espinoza, 2016; Liu *et al.*, 2022). In India, microwave drying of *Tectona grandis* (teak) resulted in a 40%–50% reduction in drying time with fewer drying-related defects, especially in thicker lumber sections (Berrocal *et al.*, 2017). Low microwave treatment of *Eucalyptus macrorhyncha* timber demonstrated a promising balance by effectively removing moisture while preserving its mechanical integrity. This approach minimized common drying defects and maintained structural properties, making it a suitable option for sensitive or high-value hardwood species where maintaining strength is crucial (Balboni *et al.*, 2018). While vacuum and microwave-assisted drying offer technical advantages, their high capital and operational costs make them less feasible in resource-constrained settings like Nepal (Espinoza and Bond, 2016). In regions like Nepal, where electricity supply is unstable and energy costs are high, some drying can be impractical. For instance, microwave drying requires precise control and uniform heating, which are difficult to achieve without advanced infrastructure. In contrast, solar kilns are low-cost, scalable (Ugwu *et al.*, 2015), and can be constructed using locally available materials, making them more suitable for rural and semi-urban areas of Nepal. Moreover, this method has been successfully evaluated in similar tropical settings, demonstrating its potential applicability to the Nepalese context.

4.2. Species-specific drying behaviors and moisture reduction

Moisture reduction during seasoning is significantly influenced by species-specific anatomical characteristics such as density, porosity, vessel structure, initial moisture content (MC), and the drying method applied (Moya *et al.*, 2012; Simpson and TenWolde, 1999). Each wood species exhibits a unique drying behavior, with varying susceptibility to defects, drying rates, and equilibrium moisture content levels (Berberović and Milota, 2011; Hwang and Oh, 2024).

Hardwoods such as *Guarea cedrata* and *Swietenia macrophylla* displayed slower drying patterns, necessitating gradual moisture removal to prevent defects such as surface checks and internal cracking. Notably, tropical hardwood species like *Dalbergia sissoo* and *Acacia nilotica* showed substantial weight loss when subjected to oven drying at elevated temperatures, indicating a higher vulnerability to moisture-induced stresses (Fatima *et al.*, 2015). This suggests techniques such as kiln, vacuum and steam-assisted drying to be effective in minimizing internal stress and surface defects while ensuring uniform moisture reduction. Variations in initial and final MC observed in temperate softwood species like *Tsuga heterophylla* and *Cryptomeria japonica* highlight the critical role of initial moisture content and wood anatomy in determining appropriate seasoning schedules. These species perform well under air drying in moderate climates, solar kiln drying with basic airflow control, and even microwave-assisted drying for small-scale or experimental applications. Most studies targeted a final moisture content below 20%, a threshold generally suitable for construction and furniture applications (Bomba *et al.*, 2014). Advanced methods such as supercritical CO_2 and vacuum drying have demonstrated efficient dewatering with minimal shrinkage in some softwood species (Dawson *et al.*, 2020; Kong *et al.*, 2018). Softwood species respond better to faster hybrid drying techniques with fewer defects, making them suitable for low-cost and energy-efficient methods. However, heartwood in these species often remained more prone to cracking due to its lower permeability. High-density hardwoods typically require longer drying durations and more sophisticated technologies to achieve uniform moisture reduction while minimizing drying defects (Bond and Espinoza, 2016; Elustondo *et al.*, 2023; McMillen and Wengert, 1978). These species are more prone to drying defects such as surface checking, internal cracking, and excessive shrinkage when dried too rapidly. Controlled kiln drying, vacuum drying, and steam-assisted techniques are therefore most effective for these woods.

After seasoning, common drying defects such as warping, end checks, internal cracks, and shrinkage were frequently reported. In Poland, kiln-dried beech wood exhibited increased cracking with higher dry bulb temperatures, highlighting the sensitivity of certain species to elevated drying conditions (Majka and Sydor, 2023). Conversely, Chinese cedar wood seasoned using superheated steam showed fewer defects compared to conventional drying methods, suggesting the advantages of steam-assisted techniques in regulating drying rates and reducing stress (Bao and Zhou, 2017). Steam and pressure treatments, particularly in Japan and China, have proven effective in minimizing internal stresses and surface splits during the drying process. For example, low-vacuum medium-temperature drying of *Cryptomeria japonica* significantly reduced warping, underscoring the method's ability to maintain dimensional stability (Jiang *et al.*, 2024). In some instances, accelerated or hybrid drying techniques, such as those employed in Australia and Bangladesh, resulted in improvements in mechanical properties, including modulus of elasticity (MOE) and modulus of rupture (MOR), despite the presence of minor drying defects (Alam *et al.*, 2022). These findings highlight the trade-off between drying efficiency and defect control, depending on species characteristics and the technology used.

Solar drying techniques were commonly employed in tropical regions such as Nigeria, Malaysia, and Central Africa, where high ambient temperatures and consistent sunlight provide favorable conditions for natural or semi-natural drying processes (Hermawan *et al.*, 2020; Owoyemi *et al.*, 2015; Simo-Tagne and Bennamoun, 2018). However, despite their low energy requirements, these methods often face limitations. Rapid moisture loss in areas with low relative humidity frequently results in uneven drying, leading to surface checking, case hardening, and overall poor wood quality (Chi *et al.*, 2024; Lamrani *et al.*, 2023). For instance, studies from Central Africa have shown that species such as *Triplochiton scleroxylon* and *Entandrophragma cylindricum* suffered dimensional instability and surface degradation due to uncontrolled solar drying (Simo-Tagne and Bennamoun, 2018). In contrast, countries located in temperate regions such as Estonia and Slovakia have adopted more technologically advanced drying systems (Dzurenda, 2020; Tamme *et al.*, 2023). These include climate-controlled kilns and air-conditioned drying chambers that offer precise regulation of relative humidity and temperature. Such systems allow for gradual moisture reduction, which significantly reduces drying defects and enhances wood quality. Dzurenda (2020) reported that beech and oak dried under controlled kiln conditions in Slovakia exhibited minimal warping and end checks, attributed to steady drying rates and optimized RH-temperature cycles.

In Nepal, where access to advanced drying infrastructure is limited, low-cost solar kilns provide a practical solution for seasoning species such as Sal (*Shorea robusta*), Sissoo (*Dalbergia sissoo*), and Uttis (*Alnus nepalensis*). Tailoring drying methods to species-specific characteristics and local economic conditions is essential for sustainable timber processing. The findings from this study will help establish clear links between appropriate drying methods and specific Nepalese wood species.

4.3. Technological trends and innovations

The evolving landscape of wood seasoning reflects a growing trend toward the integration of hybrid and innovative drying techniques, merging traditional methods with advanced technologies to optimize drying performance, reduce energy consumption, and minimize drying defects. One notable innovation is the use of supercritical CO_2 drying, particularly in countries like New Zealand (Asafu-Adjaye *et al.*, 2021; Dawson *et al.*, 2020; Pearson *et al.*, 2022; Yang and Liu, 2020). This method offers substantial promise for softwood species, as it enables rapid moisture removal while preserving cell structure. The non-thermal nature of supercritical CO_2 allows for uniform drying with minimal dimensional changes, reducing risks of warping, collapse, and internal checking (Pearson *et al.*, 2022; Yang and Liu, 2020). Dawson and Pearson (2017) demonstrated that *Pinus radiata* dried using this method exhibited excellent surface quality and consistent final moisture content, all while operating under energy-efficient conditions. This positions supercritical CO_2 as a sustainable and high-performance option, especially for high-value timber products. In North America, particularly in Canada, refinements to conventional kiln systems continue to push technological boundaries. The use of multi-step temperature and humidity regulation in heat-vent kilns has enabled more controlled moisture extraction, significantly reducing internal stresses during drying (Bergman, 2010; Glass and Zelinka, 2021). Rahimi *et al.* (2022) reported that applying a graduated temperature profile in which drying begins at lower temperatures and gradually increases resulted in consistent moisture reduction while preventing surface and internal defects in Canadian hardwoods such as *Acer saccharum* (sugar maple) and *Betula papyrifera* (paper birch). These improvements not only enhance wood quality but also optimize energy usage by minimizing over-drying.

Additionally, innovative and sustainable approaches to seasoning have emerged in countries like Spain. One notable technique involves the immersion of timber in water followed by air drying (Martínez-Gil *et al.*, 2020). This method, traditionally used for hardwoods like *Quercus ilex* and *Fagus sylvatica*, allows for the leaching of extractives and gradual moisture equalization (Bussotti *et al.*, 2002; Majka and Sydor, 2023). It provides ecological and time-saving advantages by reducing internal stresses and minimizing drying defects without compromising mechanical performance or appearance. This technique aligns with sustainable forestry and low-impact wood processing practices (Barrette *et al.*, 2023). Moreover, hybrid drying systems, which combine solar, kiln, vacuum, and microwave techniques, are gaining traction in countries like Australia, China, and India (Bond and Espinoza, 2016; Cong *et al.*, 2023; Kumar, 2024; Kumar *et al.*, 2023). These systems allow processors to start with low-energy methods (like solar or air drying) and finish with high-precision technologies (such as kiln or vacuum drying). This staged approach helps reduce energy consumption while maintaining tight control over final moisture content and drying rate. For instance, microwave-vacuum hybrid dryers are increasingly being used to dry high-density hardwoods and moisture-sensitive species, as they can accelerate drying from the core outward without inducing surface checks (Kumar, 2024; Leiker and Adamska, 2004). Artificial intelligence (AI) has been utilized in drying research and development through the application of artificial neural network (ANN) modeling and neuro-fuzzy control systems for drying process optimization (Farkas, 2024; Jumah and Mujumdar, 2005; Martynenko, 2018). A wide range of databases on material under different conditions and variability is necessary for understanding the drying performance of wood for an artificial neural network. Kato *et al.* (2022) developed a neural network to automatically classify crack severity using image processing of timber cross-sections, and machine learning was used to predict moisture content throughout the drying process (Rahimi and Avramidis, 2022). However, the application of artificial intelligence (AI) in this field remains limited due to the inherent complexity and variability of wood as a material. A large database on timber properties with integration of AI provides a greater significance in future for advancing our knowledge on timber drying, i.e. process control, timber drying rate and cracking. These technological advancements collectively reflect a global shift toward smarter, more adaptive wood drying strategies. Innovations are increasingly informed by species-specific drying behavior, energy considerations, and the growing emphasis on sustainable forestry and processing practices. With climate change and energy efficiency becoming central to industrial decision-making, the adoption of such advanced technologies will likely continue to expand.

4.4. Recommendation for sustainable and efficient seasoning in Nepal

Nepal's diverse topography and rich forest resources support a wide range of commercially and structurally important timber species, including *Shorea robusta*, *Dalbergia sissoo*, *Acacia catechu*, *Alnus nepalensis*, and *Pinus roxburghii* (Forest Research and Training Centre [FRTC], 2021; Pandey and Bajracharya, 2010). However, systematic seasoning and drying techniques for these species are largely underdeveloped. Factors such as limited research, inadequate infrastructure, and significant climatic variation across altitudes pose challenges to implementing consistent drying practices even for the same species. Traditional air-drying methods remain the predominant approach, but there is minimal data on the drying behavior of local species under Nepal's varied ecological conditions (Karki *et al.*, 2025; Pandey, 2022; Timsina *et al.*, 2021).

Given the country's altitude-driven climatic zones, a region-specific hybrid drying approach, such as combining air drying with solar kilns or employing shaded pre-drying followed by low-temperature kiln drying, is technically sound and well-suited. However, their practical feasibility in rural and semi-urban areas depends on several factors. Solar kilns, for example, are relatively low-cost and can be constructed from locally available materials, making them accessible to community forest user groups and small-scale timber processors. In contrast, low temperature kilns may require electricity or biomass-based heating, which can pose challenges in remote hill and mountain regions. To address this, alternative energy options such as solar thermal systems or improved biomass stoves could be explored to enhance energy efficiency and reliability.

In humid lowland Terai regions, solar kilns with ventilated roofing and thermal buffers are suitable, while in cooler hill areas, greenhouses or passive solar dryers can extend drying periods without rapid moisture loss. High-density species like *Shorea robusta* require moderate drying rates with careful relative humidity control, and seasonal variations such as avoiding drying during peak monsoon or winter should be considered. For medium-density species like *Dalbergia sissoo* and *Alnus nepalensis*, a combination of air seasoning followed by kiln finishing can be both cost-effective and efficient, particularly in resource-constrained rural areas (Table 4). Developing species-specific drying schedules that account for parameters such as initial moisture content, drying rate, temperature, and relative humidity is crucial for reducing defects and enhancing the mechanical properties and durability of timber. Integrating low-cost technologies, community-based training, and traditional knowledge provides a strong foundation for promoting sustainable timber drying practices in Nepal. This approach also aligned with broader sustainability frameworks contributing to SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action) and SDG 15 (Life on Land). These initiatives are consistent

Table 4. Recommended drying methods and key considerations for common nepalese timber species

Species	Recommended drying method(s)	Key technical considerations	Expected outcomes
Shorea robusta Gaertn. f. (Sal)	Kiln drying; solar kiln with relative humidity control	High-density hardwood requiring a moderate drying rate; avoid drying during monsoon or winter; highly sensitive to rapid moisture loss	Uniform moisture reduction; minimized surface checking, improved structural integrity
Dalbergia sissoo DC.	Air drying followed by kiln finishing; vacuum drying (if feasible)	Medium-density hardwood tolerant of hybrid methods; prone to warping; suitable for furniture and joinery	Reduced warping and splitting; enhanced durability; improved dimensional stability for furniture applications
Acacia catechu (L.f.) Willd	Slow solar kiln drying; shaded air drying	Dense heartwood requiring slow drying to preserve extractives and reduce cracking; used for medicinal and structural purposes	Preserved heartwood quality; minimized cracking; improved suitability for medicinal and structural uses
Alnus nepalensis D. Don.	Solar kiln drying; microwave-assisted drying	Fast-growing, low-density hardwood responsive to rapid drying; suitable for plywood and light construction	Rapid drying with retained mechanical properties; ideal for plywood and light construction
Pinus roxburghii Sarg.	Solar kiln with adequate ventilation; low-temperature kiln drying	Resinous softwood requiring temperature control to prevent resin bleeding; widely used for panelling and carpentry	Controlled resin flow, uniform moisture content; improved performance in panelling and general carpentry

with the objectives of Nepal's Forestry Sector Strategy (2016–2025), which prioritises community empowerment, value addition, and the sustainable use of forest resources. By integrating improved drying techniques into community forestry programs, Nepal can simultaneously advance economic resilience, energy efficiency, and environmental sustainability within its timber sector. This integrated approach bridges local innovation with global sustainability commitments, positioning Nepal as a model for community-based, resource-efficient wood processing.

5. CONCLUSIONS

Timber drying methods vary globally based on species type (hardwood or softwood), initial and final moisture content, and drying conditions such as temperature, relative humidity, and climate. While high-temperature drying accelerates moisture loss, it can also cause defects if not carefully managed. Conversely, slower methods minimize damage but are time-consuming. Since timber species differ in density and moisture behavior, no single drying method or condition is universally effective. This review highlights how drying conditions influence timber quality, moisture reduction, and defect occurrence across species. For Nepal, where species like *Shorea robusta* (Sal), *Dalbergia sissoo*, *Alnus nepalensis* (Uttis), and *Pinus roxburghii* (Chir Pine) are common, an integrated approach to timber drying is essential. Given the lack of systematic data on the drying behavior of Nepalese timber species, pilot studies and experimental trials should be prioritized. This should be implemented across country's major ecological zones, the Terai, Hills, and Mountains, to test species-specific drying schedules and validate the proposed hybrid methods. Comparative trials between traditional air drying and controlled techniques would help quantify gains in drying efficiency, defect reduction, and mechanical performance. In addition, species-specific moisture profiling is critical to establish accurate drying curves and equilibrium moisture content benchmarks suited to Nepal's diverse climatic conditions. Collaborative trials between the Institute of Forestry and the Forest Research and Training Centre (FRTC) can strengthen scientific capacity and guide the formulation of national standards for timber seasoning. Such coordinated efforts would ensure that future wood-drying practices are both evidence-based and technically optimized for Nepal's species and ecological diversity. Also, developing tailored drying methods will enhance wood quality, reduce losses, and boost commercial and export potential.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

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