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ENHANCING MATERIAL DURABILITY AND SUSTAINABILITY: INVESTIGATING TIMBER MOISTURE MANAGEMENT IN TIMBER STORAGE FACILITIES.

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ABSTRACT: Moisture content (MC) plays a critical role in determining the durability, structural integrity, and long-term sustainability of timber used in construction. Inadequate moisture management, especially during storage, can lead to significant deformation, decay, and loss of functionality in timber products. This study investigates timber moisture content management within storage facilities in Adelaide, South Australia, where seasonal climatic variations pose unique challenges. A mixed-methods research design was adopted, combining quantitative moisture measurements across three seasons (autumn, winter, summer) with qualitative insights derived from semi-structured interviews with eleven industry professionals. The findings highlight consistent seasonal trends, summer conditions led to over-drying while winter promoted moisture uptake, both of which deviated from the Australian standard moisture range of 10–12% for structural timber. Interview data revealed practical moisture control strategies such as indoor storage, strapping, wrapping, repacking, high product turnover, and seasonal adaptations. However, gaps remain in standardised practices for in-storage MC management, despite industry-wide reliance on sawmill compliance with initial drying protocols. The paper concludes that improved storage guidelines and context-specific strategies are crucial for optimising timber performance and supporting sustainable construction practices in climate-sensitive regions.

KEYWORDS: timber, moisture content, sustainability, timber storage, seasonal variation

1 – INTRODUCTION

Timber is increasingly recognized as a sustainable building material due to its carbon sequestration properties and relatively low embodied energy. However, the performance and longevity of timber are highly dependent on the control of its moisture content (MC), particularly during storage. Monitoring the moisture content (MC) of timber and avoiding large fluctuations is vital, as significant variation after drying can devalue the product. [1]. Research by Frese and Blaß [2] emphasized the importance of controlling wood moisture, in their study, 50 % of all investigated objects show damages or failures due to wood moisture changes or low and high wood moisture contents. Improper MC management can lead to a range of structural and aesthetic defects, compromising the material's effectiveness in construction and diminishing its environmental value. This study focuses on the storage phase of the timber supply chain, an area that has received comparatively little research attention. It seeks to identify how MC is managed during this critical phase and its implications for timber durability and sustainability in construction.

2 – BACKGROUND

2.1 TIMBER AND MOISTURE INTERACTION

Timber is hygroscopic, meaning it continuously exchanges moisture with its surrounding environment. Its moisture content changes in response to ambient humidity and temperature. These fluctuations can induce shrinkage, swelling, cracking, warping, and other forms of deformation that compromise timber's structural performance. Moisture is arguably the most important factor affecting the performance and service life of wood and wood products [3]. Water is naturally a constituent of every component of a living tree, and even after processing, traces of moisture remain within the wood cell [4].

According to AS 1684, seasoned timber intended for structural use should maintain an MC range between 10% and 15% [5], with the optimal level generally falling between 10% and 12%. Deviation from this range, even by a few percentage points, can drastically affect the product's behaviour during installation and use.

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2.2 EXISTING RESEARCH GAPS

Existing studies have primarily examined timber's behaviour during kiln drying and in-service performance. Desch and Dinwoodie [6] and Nolan, Innes [7] explored how drying methods affect MC uniformity, while more recent work by Rahimi, Avramidis [8] leverages machine learning to predict MC outcomes based on drying schedules. However, very few studies focus specifically on how MC varies during storage or how it is managed post-production. This study addresses this gap by integrating quantitative seasonal data with qualitative practitioner insights, thereby offering a fuller picture of timber's vulnerability to MC changes during storage.

3 – PROJECT DESCRIPTION

This study employed a mixed-methods approach. Quantitative data were collected across six timber storage facilities in Adelaide, measuring MC values of stored timber during autumn, winter, and summer. Each facility served as a case study. Concurrently, eleven semi-structured interviews were conducted with stakeholders in the timber industry. All interviewees had over five years of experience, with an average of 26 years, ensuring a rich dataset grounded in industry expertise.

3.1 RESEARCH QUESTIONS

1. How does timber moisture content vary with seasonal changes during storage?
2. What are the common moisture-related issues encountered in timber storage?
3. What techniques are employed by industry stakeholders to manage moisture content?

4 – MOISTURE MEASUREMENT

Moisture content measurements were conducted using a calibrated wood moisture meter (The Pinless Orion 950). The meter was applied at both ends of each timber product. The readings were then averaged per product and analysed by season. Measurements were taken at different points during autumn, winter, and summer at six storage facilities referred to as Case Studies 1 through 6. Measurements were conducted using the same methodology and instruments at all sites. The goal was to identify how environmental conditions influence moisture variability.

4.1 SEASONAL MOISTURE CONTENT TRENDS

Across all six facilities, a consistent pattern emerged in the seasonal moisture content of timber products:

- **Autumn Measurements**: Timber products generally exhibited stable MC levels, with most readings falling within the 8% to 12% range. This stability suggests that the milder and more balanced environmental conditions of autumn contribute to maintaining optimal moisture levels in timber.

- **Winter Measurements**: There was a noticeable upward shift in MC during winter, with many products recording values in the 12% to 14% range, and some even reaching the 14% to 16% bracket. This increase is likely due to the higher ambient humidity and lower temperatures characteristic of winter, which can lead to increased moisture absorption by timber.

- **Summer Measurements**: The data indicated a decrease in MC during summer, with many products showing readings below the 10% threshold. The higher temperatures and lower humidity typical of summer likely facilitate moisture loss from timber, leading to these reduced MC levels.

These seasonal trends reveal the importance of adjusting storage and handling practices for timber products throughout the year to mitigate the impact of environmental conditions on moisture retention.

4.2 MOISTURE CONTENT VARIABILITY PATTERNS

The analysis also revealed patterns in moisture content variability across the seasons:

- **Autumn**: A significant number of timber products displayed minimal variability, with differences between measurements at both ends often falling below 0.5%. This consistency aligns with the stable environmental conditions prevalent during autumn.

- **Winter**: There was an increase in moisture variability, with many products exhibiting differences exceeding 1.5%. The elevated ambient humidity and reduced airflow during winter may contribute to these inconsistencies in moisture distribution within the timber.

- **Summer**: While the average moisture content was lower, variability remained notable. Some products showed differences greater than 1.5%, possibly due to uneven drying rates influenced by high temperatures.

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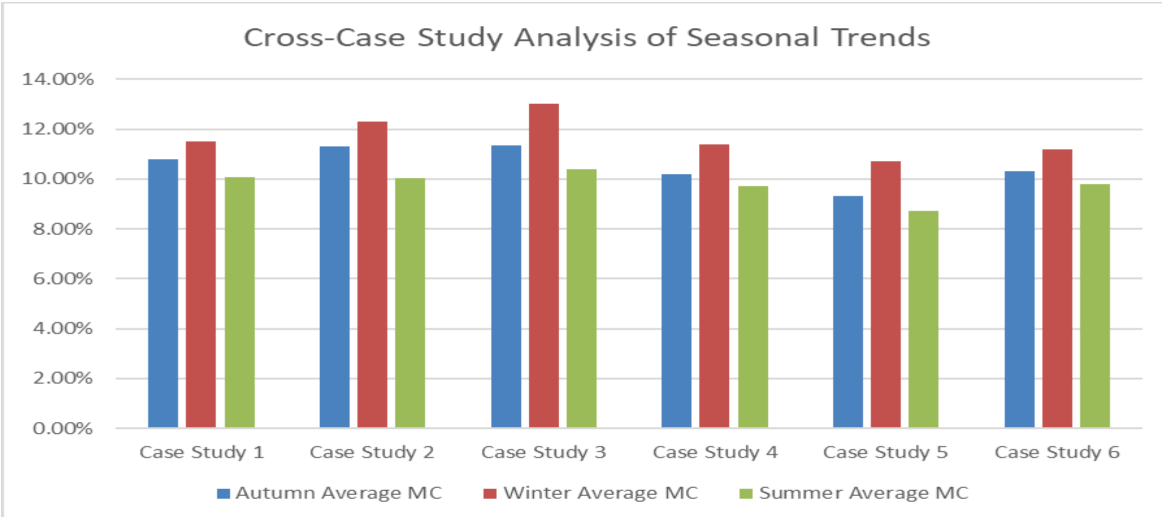

Figure 1: Seasonal Average Moisture Content Across All Case Studies.

4.3 OVERVIEW OF DEVIATION ANALYSIS ACROSS CASE STUDIES

Evaluating the moisture content measurements against the Australian Standard (10% to 12%) for construction applications, revealed seasonal deviations.

- **Autumn:** Many samples fell within or just below the standard range, indicating general compliance and suggesting that the environmental conditions during this season are conducive to maintaining recommended moisture levels.
- **Winter:** There was a significant increase in the proportion of samples exceeding the standard range. This suggests that the cooler and more humid conditions of winter make it challenging to adhere to the recommended MC levels.
- **Summer:** While fewer samples exceeded the standard range, there was an increase in the number of samples falling below it. This trend indicates a risk of over-drying during the hot and dry summer months, which could compromise the structural integrity of timber if not properly managed.

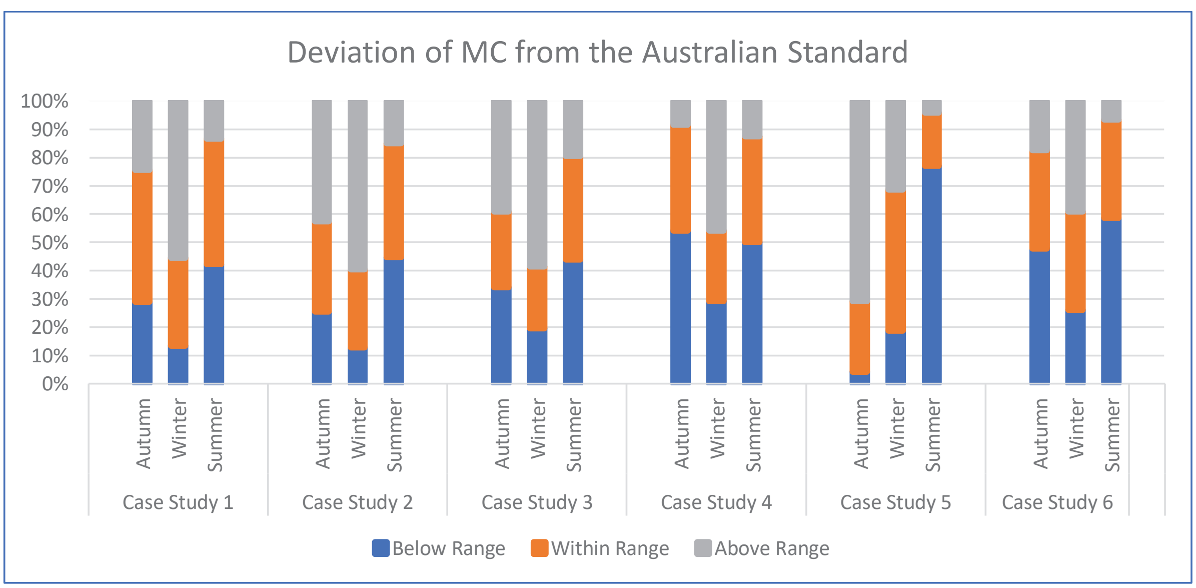

Figure 2: Deviation from Australian Standard of Timber Average Moisture Content Across Case Studies.

These deviations from the standard across different seasons highlight the critical need for seasonally adjusted storage and handling protocols to maintain timber quality and ensure compliance with industry standards.

4.4 COMPARATIVE ANALYSIS OF CASE STUDIES

Comparative analysis using box plots as shown in figure 3 above showed how moisture levels varied across the six case studies and seasons, providing a visual understanding of both central tendencies and deviations. The shows the box plots that displays the descriptive statistics of MC across three seasons in the six case studies.

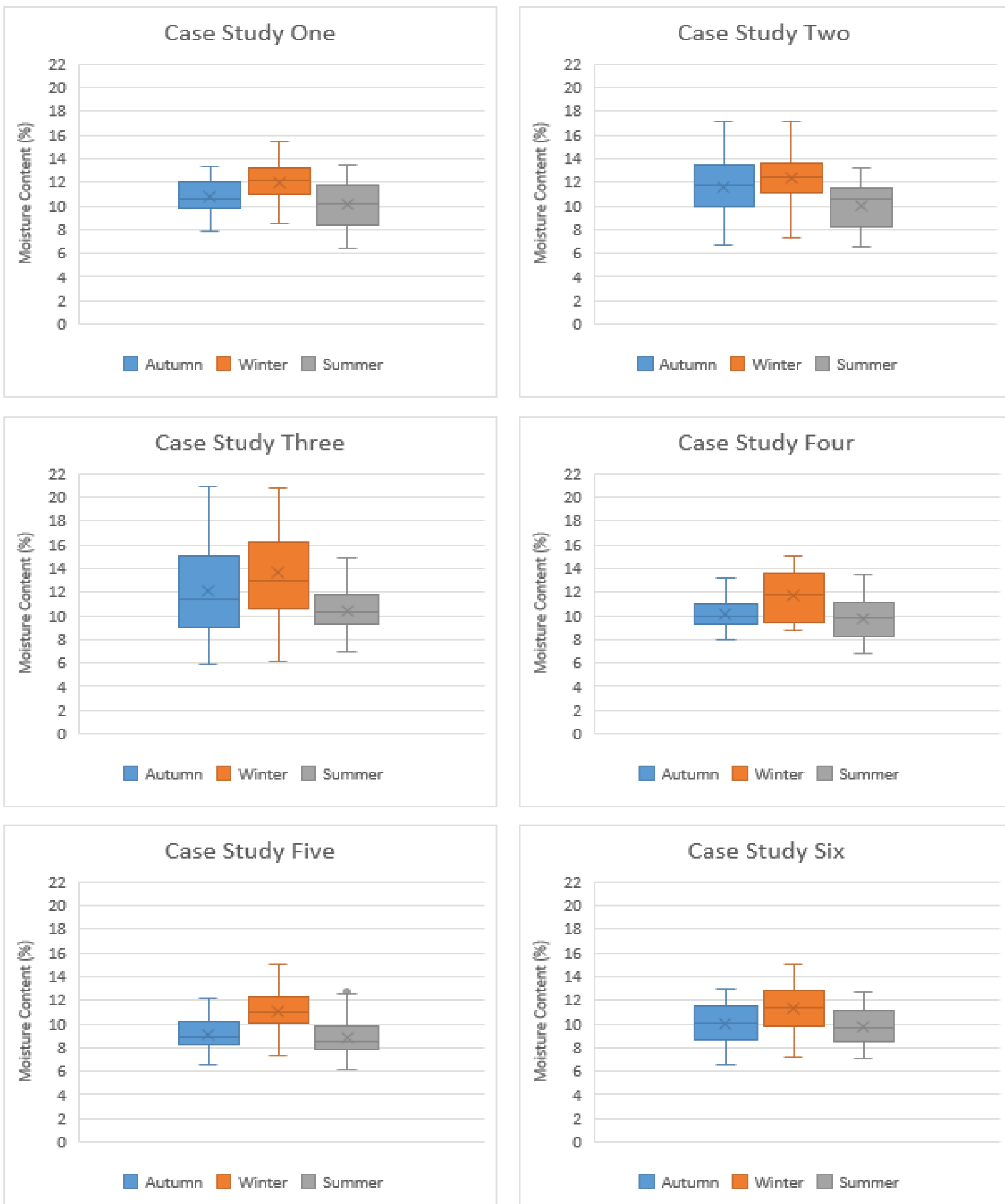

Figure 3: Boxplots showing the relationship between seasons and case studies

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5 – INDUSTRY STAKEHOLDER INSIGHTS

Eleven semi-structured interviews were conducted with experienced stakeholders in the timber storage industry in South Australia. Interviews were transcribed, coded using NVivo 14, and analysed thematically. Insights were organised into key themes including moisture control practices, issues, standards, seasonal challenges, and recommendations.

5.1 TIMBER MOISTURE MANAGEMENT PRACTICES

The importance of managing moisture content during the storage of timber was highlighted as a critical factor in ensuring timber quality. Participants agreed that improper moisture management could lead to significant issues that affect timber's structural integrity and usability. One interviewee emphasized this point by stating, *"Maintaining optimal moisture levels plays a very significant role. It keeps the stability. If you don't manage the moisture, you send out unstable timber"*. This view was echoed by other participants who pointed out that timber must be kept at an appropriate MC level to prevent deformities such as warping, cracking, and swelling.

Interviewees indicated that the optimal MC range for timber is generally between 10% and 12% after kiln drying. This range ensures that the timber is neither too dry, which could make it brittle, nor too moist, which could make it prone to warping and decay. However, maintaining this balance during storage, especially in open or outdoor facilities, poses challenges. Timber stored outdoors is particularly vulnerable to fluctuations in air humidity and temperature, leading to potential moisture reabsorption or excessive drying.

Most participants described using basic methods such as wrapping timber in plastic and strapping bundles together to minimize exposure to environmental factors. One interviewee explained, *"We strap and wrap everything to make sure it stays stable. The plastic protects it from rain, and the strapping helps to keep it from moving around"*. While these methods are effective to a degree, some participants acknowledged that they were not foolproof, as damage could still occur if the plastic was ripped, or the timber bundles were left exposed to extreme conditions for too long.

Another key practice mentioned was the importance of high turnover rates. Several participants emphasized that minimizing the length of time timber spends in storage is crucial for reducing the risk of moisture-related problems. One interviewee noted, *"The quicker we turn timber over, the less chance it has to fluctuate in moisture"*. Participants explained that by ensuring timber does not sit in storage for extended periods, they can limit its exposure to the elements and maintain its quality.

5.2 MOISTURE-RELATED ISSUES IN TIMBER STORAGE

All participants expressed concerns over common moisture-related issues in stored timber, with warping, cracking, and mold growth being the most frequently mentioned problems. Some interviewees pointed out that these issues often arise when timber is exposed to environmental changes during storage. One interviewee shared, *"Moisture levels change based on the seasons. If you store timber through the hot summers, you get warping. In the cooler, damper months, mold becomes more of an issue"*.

Participants emphasized that both too much and too little moisture can lead to serious problems. Excessive moisture, often caused by high humidity or improper protection during storage, can lead to swelling, mold, and fungal growth. As one interviewee noted, *"If the timber gets too wet, especially in a humid environment, it starts to rot and we lose it entirely".* On the other hand, drying timber too quickly, particularly during hot summer months, can cause it to become brittle and crack. These issues not only reduce the structural integrity of the timber but also lead to financial losses for suppliers and distributors, as the affected timber may no longer meet quality standards for use in construction. Below are the key moisture-related issues identified by the participants:

- Warping and twisting
- Shrinking and cracking
- Cupping and bowing
- Mould and fungal decay
- Insect infestation (especially termites)
- Swelling

5.3 THE ROLE OF INDUSTRY STANDARDS IN MC MANAGEMENT

While all participants agreed on the importance of managing MC, they also noted that industry standards largely govern moisture control at the sawmill stage, where timber is kiln-dried to meet Australian standards. These standards ensure that timber leaves the sawmill at the correct moisture level, typically between 10% and

12%. As one interviewee explained, *"Australian standards make sure sawmills dry their timber to a specific range, and that's generally good enough for us to start with"*.

However, several interviewees indicated that these standards do not extend to the storage phase, where MC can fluctuate due to environmental factors. One interviewee pointed out, *"Once the timber leaves the mill, there's no strict regulation on how it should be stored, which leaves room for a lot of variability"*. This inconsistency was seen as a gap in the industry, particularly because the storage environment plays a critical role in maintaining timber quality.

Although most participants felt confident in the kiln-drying process at sawmills, they suggested that more could be done to create standardized guidelines for timber storage to ensure that moisture levels remain within acceptable limits during this phase. One interviewee emphasized that *"It's up to each facility to manage moisture during storage, and that leads to different results depending on how it's done"*. Some interviewees proposed that real-time moisture monitoring systems could help bridge this gap by providing immediate feedback on timber conditions during storage.

5.4 SEASONAL IMPACT ON MOISTURE CONTENT MANAGEMENT

The impact of seasonal variations on MC was a recurring theme in the interviews. Participants observed that timber's moisture levels are highly sensitive to environmental changes, particularly during the hot and dry summers in South Australia. One interviewee shared, *"During the summer, we have a lot more issues with warping because the timber dries out too quickly"*. Similarly, another participant added, *"Winter brings its own challenges. There's more moisture in the air, so mold and decay are bigger concerns during the colder months"*.

These seasonal effects were seen as significant contributors to the overall moisture-related problems in timber storage. Timber that is not adequately protected from seasonal changes may experience rapid fluctuations in moisture levels, leading to deformation and degradation. Participants highlighted that adjusting storage practices based on the season, such as using additional coverings in winter or increasing ventilation in summer, could help mitigate these effects.

5.5 MOISTURE CONTROL TECHNIQUES DURING STORAGE

In response to the challenges posed by moisture fluctuations, participants shared various techniques they use to control MC during storage. Participants recommended the following practices: These included strapping and wrapping timber, storing it off the ground, and maintaining high turnover rates to reduce the amount of time timber is stored.

Participants recommended the following practices:

- **Kiln Drying**: Ensures timber is dried to 10–12% MC before delivery.
- **Strapping & Wrapping**: Protects against movement and external moisture.
- **Indoor/Covered Storage**: Prevents exposure to sun and rain.
- **Proper Stacking and Storage Conditions:** Allow for air circulation and prevent moisture buildup.
- **High Turnover of Stock**: Reduces the time timber is exposed to fluctuating conditions.
- **Storing Off the Ground**: Prevents moisture absorption from the ground.
- **Repacking**: Essential after timber packs are opened.

5.6 RECOMMENDATIONS FOR IMPROVED MC MANAGEMENT

Participants were also asked to share their recommendations for improving MC management during storage. Many suggested that developing industry-wide guidelines for storage practices, particularly in regard to moisture control, would be beneficial. An interviewee proposed that *"There should be more standardized practices for how timber is stored, especially when it comes to managing moisture content during different seasons"*.

Several participants also recommended the adoption of advanced technologies, such as real-time moisture monitoring systems. One interviewee emphasized *"If we had better tools to monitor moisture levels, we could take action earlier to prevent damage. That would save us a lot of time and money in the long run"*.

Additionally, participants suggested that more training and education on moisture management would help raise awareness across the industry. One interviewee noted, *"Not everyone fully understands how moisture affects timber. More education on this could really improve storage practices and timber quality"*.

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6 – RESULTS AND DISCUSSION

The findings from both the quantitative and qualitative phases of this research are synthesized to provide a cohesive understanding of how moisture content (MC) fluctuates in timber during storage and industry professionals manage these challenges. By integrating data from the six case studies (quantitative) with insights from the eleven stakeholder interviews (qualitative), this discussion highlights the complexities of moisture control in the timber supply chain and offers reflections on how these insights align with existing literature.

6.1 SEASONAL VARIATIONS IN MOISTURE CONTENT

Across all six case studies, autumn measurements generally exhibited more stable moisture levels, with most samples falling within an 8%–12% range. This stability was further corroborated by interviewees who noted that autumn's milder temperatures and relatively balanced humidity reduce moisture fluctuations. This finding aligns with Richards and Brimblecombe [9], who observed that moderate climates lead to less drastic MC swings. The interviews suggested minimal need for extra interventions in autumn, beyond standard storage measures (e.g., indoor storage and protective wrapping).

In contrast, winter showed a clear upward shift in MC. The quantitative data revealed a higher proportion of samples exceeding the recommended 10–12% range. Participants in the qualitative phase described winter as a period of elevated humidity and reduced ventilation, conditions conducive to moisture uptake in timber [10]. Several respondents emphasized that indoor storage, protective coverings, and high turnover mitigate these risks but admitted that extended cold, damp conditions can still lead to warping, mold growth, and other forms of deterioration if moisture remains unchecked. These observations mirror Fredriksson [11] contention that cooler, more humid conditions pose particular challenges for timber stability.

Although winter introduced higher MC levels, the quantitative data also highlighted potential over-drying in summer, with many samples dropping below 10%. Interviews reinforced this: multiple participants explained that high temperatures and strong sunlight in Adelaide can accelerate moisture loss, increasing the risk of cracking, splitting, and structural weakening. This echoes Hu, Qi [12], who found that prolonged exposure to heat leads to excessive moisture evaporation. Respondents pointed out that storing timber in direct sunlight, even briefly, can cause dramatic changes. Nonetheless, some facilities employ "high turnover" strategies or keep timber under cover to limit exposure times.

6.2 ROLE OF SAWMILLS AND STANDARDS

A central theme was the heavy reliance on sawmills to ensure timber arrives with an appropriate MC. Interviewees consistently expressed trust that sawmills follow Australian standards, specifically AS 1684 for Residential Timber-Framed Construction, by kiln-drying timber to 10–12%. The quantitative data showed that initial MC was generally within or near this range, supporting participants' claims. Yet, once timber enters storage, the study found no universal standard for ongoing MC management. This gap can lead to post-production moisture fluctuations that degrade product quality.

While sawmills appear to meet the Australian standard for initial moisture content, the interviews suggest that actual in-storage practices vary widely. Some participants keep meticulous track of temperature and humidity, while others rely on basic checks. The quantitative findings of seasonal deviations from the 10–12% range indicate that meeting standards at the mill does not guarantee compliance by the time timber is used. This discrepancy highlights the need for additional guidelines focusing on ***storage-phase moisture management***, an area not comprehensively covered by AS 1684.

6.3 INTEGRATING QUANTITATIVE AND QUALITATIVE INSIGHTS

By triangulating the data, the following integrated conclusions emerge:

1. **Season-Specific Risks**:
   - *Quantitative*: Sharp increases in MC in winter and a risk of over-drying in summer.
   - *Qualitative*: Industry professionals confirm they see more warping in hot summers and more mold or swelling in wet winters.
2. **Preventive Strategies**:
   - *Quantitative*: Facilities with consistent coverage, strapping, and minimal ground contact reported more stable MC readings.
   - *Qualitative*: Interviewees praised strapping and wrapping, high turnover, and indoor storage as critical moisture-control techniques.
3. **Regulatory Reliance**:

- *Quantitative*: Initial MC often near the 10–12% standard, but seasonal deviations were common.
- *Qualitative*: Interviewees rely heavily on mills to meet standards but see little standardized guidance for the storage phase.

4. **Technological Shortcomings**:

- *Quantitative*: Rapid MC changes in certain facilities highlight the need for continuous monitoring.
- *Qualitative*: Many interviewees noted the lack of real-time sensors, expressing interest in more advanced monitoring but citing cost concerns.

6.4 IMPLICATIONS FOR PRACTICE AND POLICY

1. **Enhanced Storage Guidelines**: The findings indicate a pressing need for more explicit storage-phase standards or guidelines to supplement AS 1684. These could address ideal humidity levels, recommended storage durations, and best practices for packaging integrity.

2. **Seasonal Adaptations**: Storage facilities might implement climate-specific adjustments, such as installing dehumidifiers in winter or providing partial shading in summer, to reduce moisture extremes.

3. **Invest in Monitoring Technologies**: Although cost is a barrier, real-time sensor systems would help storage managers detect subtle MC fluctuations, facilitating proactive measures before significant damage occurs.

4. **Importer Vigilance**: Interviewees noted that imported timber can be especially prone to MC issues due to environmental shifts. This calls for stricter checks at entry points and possibly requiring overseas mills to meet the same drying protocols as domestic mills.

7 – CONCLUSION

This research has illuminated the critical role of moisture content management in timber storage, demonstrating how seasonal variations, storage practices, and real-time monitoring (or lack thereof) shape timber's structural integrity and usability. By integrating both quantitative data from six case studies and qualitative insights from industry professionals, the study provides a comprehensive view of current challenges and practical solutions.
Although the research reveals the complexity of managing moisture throughout the timber supply chain, it also offers clear strategies, ranging from high turnover and covered storage to advanced moisture monitoring systems, that can significantly mitigate moisture-induced degradation. The findings show a pressing need for standardized guidelines that go beyond the mill to govern moisture control during storage, transportation, and final use.

Ultimately, improved moisture management in timber storage not only enhances the quality and longevity of timber products but also supports the broader sustainability goals of the construction industry. Future research could systematically track how small fluctuations (±2–3% MC) affect structural performance. By addressing the identified gaps in this study, particularly in storage guidelines, stakeholders can ensure that timber remains a reliable, eco-friendly building material in the face of changing environmental and market demands.

Data Availability Statement: Data generated or analysed during the study are available from the corresponding author upon request.

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