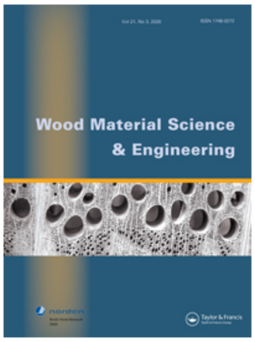

Wood Material Science & Engineering

ISSN: 1748-0272 (Print) 1748-0280 (Online) Journal homepage: www.tandfonline.com/journals/swoo20

Roundwood storage methods and their effect on spruce wood quality: a review

Stephan Böhm, Axel Solt-Rindler, Oliver Vay, Robert Prinz, Michael Grabner & Christian Kanzian

To cite this article: Stephan Böhm, Axel Solt-Rindler, Oliver Vay, Robert Prinz, Michael Grabner & Christian Kanzian (06 Jul 2026): Roundwood storage methods and their effect on spruce wood quality: a review, Wood Material Science & Engineering, DOI: 10.1080/17480272.2026.2682454

To link to this article: https://doi.org/10.1080/17480272.2026.2682454

Published online: 06 Jul 2026.

WOOD MATERIAL SCIENCE & ENGINEERING
https://doi.org/10.1080/17480272.2026.2682454

REVIEW ARTICLE

OPEN ACCESS Check for updates

Roundwood storage methods and their effect on spruce wood quality: a review

Stephan Böhm [a], Axel Solt-Rindler [b,c], Oliver Vay [b,c], Robert Prinz [d], Michael Grabner [b] and Christian Kanzian [a]

[a]BOKU University, Institute of Forest Engineering, Department of Ecosystem Management, Climate and Biodiversity, Vienna, Austria; [b]Wood K plus – Competence Centre for Wood Composites & Wood Chemistry, Kompetenzzentrum Holz GmbH, Linz, Austria; [c]BOKU University, Institute of Wood Technology and Renewable Materials, Department of Natural Sciences and Sustainable Resources, Tulln an der Donau, Austria; [d]Natural Resources Institute Finland (Luke), Joensuu, Finland

ABSTRACT

Climate-driven increases in calamities are altering timber supply dynamics across Europe, resulting in large volumes of spruce roundwood that cannot be processed immediately. Interim storage buffers timber supply and helps maintain wood quality. Storage decisions involve trade-offs among economic cost, environmental impact, operational feasibility and wood-quality preservation, yet the available knowledge is dispersed across technical and scientific literature.

This review synthesises published research on spruce roundwood storage based on 68 studies spanning six decades. Storage methods were classified and evaluated using an integrated framework of biological, chemical and physical quality indicators. The reviewed literature shows that storage conditions, particularly the interaction of moisture availability, oxygen supply, and temperature, govern wood quality development. Dry storage is scalable but offers only short protection. Wet and anaerobic foil storage enable reliable long-term preservation but require higher technical effort. Cold storage is effective yet geographically and seasonally constrained, while live or standing storage provides limited and unpredictable preservation.

Overall, no method is universally optimal, but each represents a specific preservation regime with defined operational limits. By linking storage environment to resulting wood condition, this synthesis provides a structured reference for interpreting quality development and selecting suitable storage strategies for spruce roundwood during interim storage.

ARTICLE HISTORY
Received 5 March 2026
Revised 8 May 2026
Accepted 26 May 2026

KEYWORDS
Norway spruce round timber; wood quality development; storage-induced degradation; salvage timber management

1. Introduction

The forest-based supply chain is increasingly challenged by the rising frequency and severity of natural disturbances, with average annual damage volumes of 43.8 million m^3 per year between 1950 and 2019 across Europe (Patacca *et al*. 2023). Sudden events such as droughts, storms and subsequent bark beetle outbreaks generate unanticipated volumes of timber, resulting in supply shocks that affect roundwood prices negatively (Schwarzbauer 2006). Fuchs *et al*. (2022) distinguish two causes of revenue loss after a disturbance, namely a decline in roundwood quality and a temporary oversupply in the market. For spruce (*Picea* spp.) roundwood in particular, the study identified the latter as the main driver of reduced revenues. Asada *et al*. (2023) analysed the differential effects of disturbance events on coniferous roundwood assortments. While windthrow and bark beetle outbreaks led to decreased pulpwood prices, salvage logging tended to increase prices for high-quality sawlogs, particularly in regions where sawlog exports are of minor importance.

Beyond price elasticity, logistical constraints represent an additional challenge for the forest-based supply chain in the aftermath of large-scale disturbances. Depending on the season, the risk of bark beetle infestation and mass propagation is high, as damaged stands are especially susceptible to colonisation and provide suitable breeding material (Christiansen and Bakke 1988, Senf and Seidl 2021, Kärvemo *et al*. 2023). Consequently, resources must be reallocated to salvage logging operations, and operational decisions regarding the prioritisation of affected stands are required (Roos 2023). A considerable proportion of the roundwood cannot be immediately processed and must therefore be stored in interim facilities. Depending on the extent of the damage and the resulting timber volumes, storage periods may extend over several years. During interim storage, wood quality deteriorates, leading to a decline in economic value. Exposure to environmental factors and biological agents such as insects, fungi and bacteria are the main drivers of this degradation. The responsibility for timber storage and, by extension, the associated risk of quality and value loss typically lies with the forest owner.

Several methods for roundwood storage have been developed to mitigate degradation processes and preserve wood value during interim storage. Increasing costs and changing environmental regulations necessitate the selection of optimal storage solutions in the event of calamities, balancing

CONTACT Stephan Böhm stephan.boehm@boku.ac.at BOKU University, Institute of Forest Engineering, Department of Ecosystem Management, Climate and Biodiversity, Peter Jordan Strasse 82, Vienna, 1190, Austria
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

treatment costs against the potential loss in preserved timber value, or the development of new methods for roundwood preservation. Although numerous guidelines (CTBA 2004, Lukkari *et al*. 2004, Lutze 2014) and national reports (Mäkelä and Pennanen 1980, Mäkelä *et al*. 2000, Mäkelä *et al*. 2001, Mäkelä 2002, Mäkelä and Achren 2003, Mäkelä 2004, Golser *et al*. 2005, Wilhelmsson *et al*. 2010) for roundwood storage have been developed over recent decades, structured reviews synthesising scientific studies that link specific storage methods with their preservation outcomes remain scarce. The objective of this review is to provide a comprehensive overview of published research addressing the effects of different storage methods and stock treatments on the quality of spruce (*Picea* spp.) roundwood.

2. Methods

2.1. Literature search and selection

The literature search was conducted in multiple steps. In an initial step, a systematic approach was employed to identify relevant literature on the storage of spruce wood as roundwood. A comprehensive search was conducted using major academic databases, including Scopus, Web of Science and Google Scholar.

Search strings with Boolean operators were used to combine relevant keywords such as "spruce", "Picea", "roundwood", "log storage" and "wood preservation". The strings were iteratively expanded and refined. For example, it was necessary to incorporate an 'AND NOT'- operator to exclude literature that primarily focuses on carbon storage. A final string, which is specifically tailored to search within the title, the abstract and the keywords in the database Scopus is provided as an example in Table 1. The translation of the string to the required syntax of the data-bases Web of Science and Google scholar was done with the help of ChatGPT (OpenAI 2023).

The titles and abstracts of all retrieved articles were screened to assess their relevance to the topic. Studies were included if they (1) focused specifically on spruce (*Picea* spp.) wood, (2) addressed its storage as roundwood and (3) addressed aspects of wood quality. Studies were excluded if they (1) focused on other wood species, (2) investigated further processed forms of wood (e.g. sawn timber, chips, pellets) or (3) did not address storage or storage-related effects on wood quality. No time range was applied to the search criteria and all available studies were considered for inclusion. After initial screening, the full texts of potentially relevant studies were retrieved (where available) and further assessed for eligibility. In addition, the reference lists of the included articles were manually searched to identify further relevant studies which were not listed in the aforementioned databases. This snowballing technique ensured that relevant literature was considered which was not found by the initially performed systematic search approach, but does meet the scope. A small number of cited studies could not be obtained in full text, but their abstracts and secondary citations were reviewed to minimise potential gaps in coverage.

Table 1. The final search string used in Scopus to identify relevant literature employed the Boolean operators 'AND', 'OR', and 'AND NOT', along with the asterisk (*) wildcard to capture variations in word forms, including different inflections, plural forms and parts of speech.

TITLE-ABS-KEY (("round*wood" OR "log*wood" OR "log*" OR "timber*" OR "lumber*" OR "wood*log")
AND ("spruce" OR "Picea") AND ("store" OR "storage" OR "stor*method*" OR "stor*technique*" OR "stor*practice*" OR "stor*condition*" OR "wet*stor*" OR "dry*stor*" OR "foil*stor*" OR "in*bark" OR "with*bark" OR "de*bark*" OR "bark*free" OR "without*bark" OR "bark*remov*" OR "preserv*method*" OR "conserv*method*" OR "wood*stor*" OR "log*stor*" OR "wood*preserv*" OR "log*preserv*" OR "moist*stor*" OR "humid*stor*" OR "air-dry*stor*" OR "kiln-dry*stor*" OR "water*stor*" OR "submerg*stor*" OR "wrap*stor*" OR "seal*stor*" OR "cover*stor*" OR "bark*intact" OR "bark*on" OR "bark*stripp*" OR "bark*peel*" OR "blue*stain*" OR "sap*stain*" OR "discolor*" OR "discolour*"))
AND NOT ("store W/2 carbon" OR "storage W/2 carbon" OR "carbon W/ store" OR "carbon storage")

It was found that many of the references identified origin from Germany and Scandinavia. As the authors of this review speak German and Finnish in addition to English, it was worth taking a look into literature written in these languages. This includes not only peer-reviewed literature in SCI-listed journals, but also many sources published in weekly specialist journals or as reports, which provide data that seem relevant. Given the applied nature of roundwood storage research and the historical importance of regional trials, this review adopts a systematic core search complemented by targeted inclusion of high-relevance technical and regional sources.

2.2. Analytical framework

The categorisation applied in this work builds on recent scientific classifications of roundwood storage (Trautwein *et al*. 2025b), is complemented by the addition of cold storage, and is further refined by distinguishing between deliberate, technically implemented storage methods and situational storage options arising from operational constraints. This distinction is necessary because live and standing storage do not constitute actively controlled preservation strategies. Moreover, in these cases the material does not formally qualify as roundwood according to the Joint Forest Sector Questionnaire forest products definitions (FAO 2021), as the trees remain unharvested. Both may occur as viable situational options when harvesting or processing capacities are exceeded and therefore differ fundamentally from storage methods with defined mechanisms. They are mentioned in this review for conceptual completeness, but are not incorporated into the analytical framework of storage effects because, in these cases, biologically induced degradation processes cannot be linked to a defined and controllable storage environment. Although biological agents also drive quality changes in managed storage systems, live and standing storage lack clear temporal, physical, and environmental boundaries, and wood-quality development is dominated by disturbance-related processes – particularly bark beetle attack and associated fungal succession – rather than by storage-induced conditions.

To enable a structured evaluation of spruce wood quality development during storage, all identified parameters in the reviewed literature were categorised into three principal domains: (1) biological, (2) chemical, and (3) physical quality indicators. This classification focuses on state-based indicators describing the material condition of the wood. Many indicators were linked to a corresponding observable effect, for instance discolouration, surface cracking, or chemical alteration, which serves as a practical manifestation of wood quality change. Indicators include intrinsic material properties while environmental parameters are treated separately as process-based indicators governing quality development. This framework provides a consistent basis for comparing findings across studies and storage methods, enabling a systematic interpretation of how different preservation environments influence spruce roundwood integrity.

In a subsequent synthesis step, the qualitative evidence derived from these indicator domains is integrated into a comparative, method-level assessment. This synthesis is expressed using an ordinal, multi-criteria radar chart that aggregates literature-based tendencies across major storage methods rather than representing measured performance values. The radar chart builds directly on the analytical framework by condensing biological, chemical, and physical effects into six comparative criteria reflecting economic, environmental, operational, and preservation-related trade-offs. Each author independently rated the storage methods across the six criteria, and the final scores represent the arithmetic mean of these ratings. Sub-methods are thereby considered as sources of variability within each storage method, while the synthesis focuses on general performance envelopes at the method level.

3. Results

3.1. Relevant storage methods

The literature search and subsequent screening process resulted in 68 publications, relevant to this review. The earliest identified study dates back to 1966 (Dahm 1966), while the most recent contribution was published in 2026 (Trautwein *et al*. 2026), indicating a research period spanning six decades.

As shown in Figure 1, the temporal distribution of studies is highly uneven and strongly associated with disturbance-driven research waves. Isolated early contributions appeared between the 1960s and late 1980s, mainly addressing water storage and basic dry storage effects. A first marked increase in publications occurred in the early 1990s, coinciding with the large-scale storm events *Vivian* and *Wiebke* (1990 (Groß *et al*. 1993)). Further pronounced clusters follow the storms Lothar (1999 (Anonymous 2006)), Gudrun (2005 (Jonsson 2008)), Kyrill (2007 (Geibler and Scholz 2008)), Friederike (2018 (Brischke *et al*. 2020)) and Sabine (2020 (Anonymous 2020b)), reflecting recurring surges in research activity triggered by calamity-related timber oversupply. Since approximately 2000, studies on spruce roundwood storage have appeared continuously, with a noticeable intensification after 2010, indicating sustained relevance under changing climatic and disturbance regimes.

With respect to storage methods (Figure 2), dry storage is addressed in the largest number of studies, appearing in 31 publications. Within this category, uncovered piles dominate clearly, whereas covered dry storage (including tarpaulins, roofed piles, and indoor storage) is treated in a substantially smaller number of studies, often in combination with drying-oriented or engineered conservation concepts. Wet storage is the second most extensively investigated category, with 26 studies, most of which focus on sprinkling systems, while full water storage is addressed in only five studies, all of which are comparatively early and experimentally oriented.

Foil storage is represented by 12 sources, almost exclusively originating from Central Europe and largely concentrated around the development and evaluation of foil and wet storage during and after the 1990s. Cold storage appears in four studies, exclusively from Finland, and is closely linked to winter-harvested pulpwood. Bio-chemical treatments and in-ground storage are each addressed in only 4 and 2 studies, reflecting their specialised application and limited operational relevance.

Geographically, the reviewed literature is strongly concentrated in Central and Northern Europe, with the majority of studies originating from Germany, Sweden, Finland, complemented by smaller numbers of studies from Austria, Norway, Switzerland, Slovakia, the United Kingdom, Canada, and Greece. This regional focus reflects both the ecological importance of spruce and the historical role of storm and bark-beetle disturbances in these regions.

Overall, the distribution of studies reveals a pronounced methodological and temporal bias. Research activity seemingly intensifies following large disturbance events and focuses primarily on storage methods that are either widely applied in practice (dry storage, sprinkling) or demonstrably effective but technically demanding (water storage and foil storage). In contrast, storage methods with narrower operational applicability or higher technical complexity remain underrepresented, despite their potential relevance under specific climatic, ecological, or logistical constraints.

3.2. Quality indicators

The reviewed studies report a wide range of biological, chemical, and physical indicators that have been used to assess the quality of spruce (*Picea* spp.) roundwood under different storage conditions. These indicators describe the material state of the wood and its observable responses to storage environments. Beside these state-based indicators there are grading systems mentioned in the literature that translate wood condition into market-relevant classes.

3.2.1. Biological quality indicators

Biological quality indicators describe the range of fungal, bacterial, and insect-related processes that affect spruce roundwood during storage. Assessments capture both the presence of specific organisms such as *Armillaria* spp., blue-stain fungi, moulds, wood rot fungi and a variety of phenomenological decay types that reflect changes in wood structure or appearance. Together, these indicators represent the main biological pathways through which roundwood deteriorates under different storage environments.

The terminology used in the sources combines mechanistic and descriptive perspectives, which can lead to inconsistencies if not clarified. Brown rot and white rot denote well-defined enzymatic decay mechanisms that modify lignin and polysaccharides in characteristic ways. While soft rot is defined by

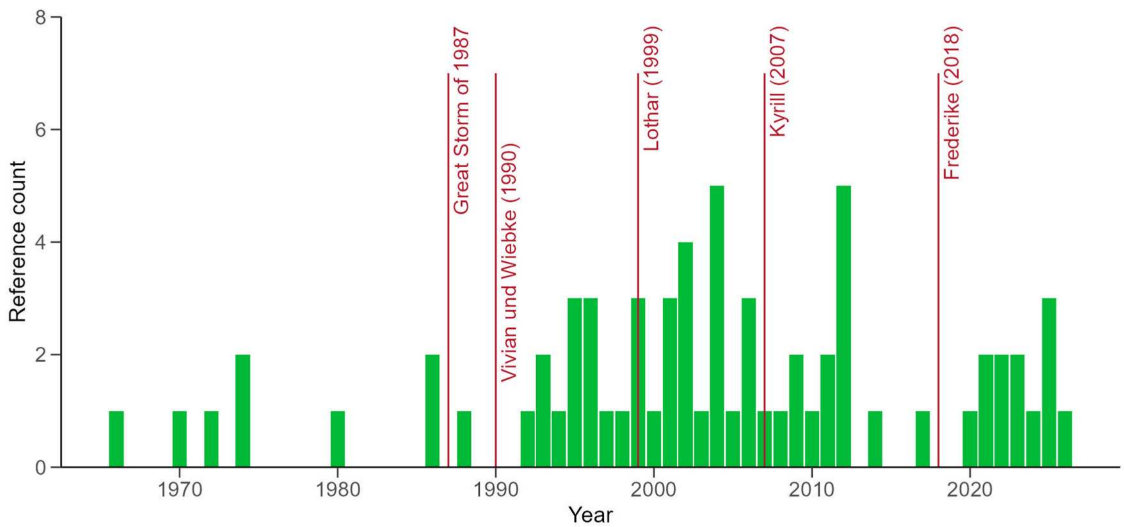

Figure 1. Reference count by publication year and storm events, which were referenced within the reviewed literature.

characteristic cell wall degradation patterns, including cavity formation and erosion, first described by Savory (1954), the term is used inconsistently in the reviewed literature and is often applied descriptively in practice to denote superficial or visually softened wood, rather than a distinct decay mechanism. Discolouration phenomena such as blue-stain and red-streak are similarly not structural forms of decay but visual effects caused by fungi that colonise nutrient-rich sapwood. For the purposes of this review, these descriptors are treated as complementary indicators spanning aesthetic alterations, early-stage degradation, and advanced rot, irrespective of whether the underlying fungi or decay mechanisms were explicitly identified in the original studies.

This classification provides a consistent basis for interpreting biotic activity across storage methods. Table 2 summarises all identified biologic indicators together with their observable effects, the assessment methods applied, the storage methods in which they were reported, and the corresponding references.

Insect infestation under dry storage conditions involved bark beetle (e.g. *Ips typographus* (L.)) as well as boreholes from wood-boring insects such as various species of longhorn beetles (*Cerambycidae*), ambrosia beetles (e.g. *Trypodendron lineatum* (Oliv.)), and wood wasps (*Siricidae*). Damage was quantified through borehole and gallery counts on stem sections, often in conjunction with assessments of fungal colonisation.

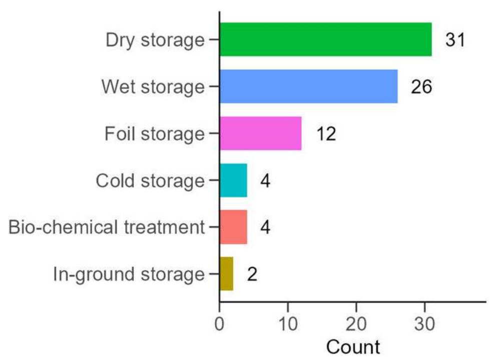

Figure 2. Count of reviewed sources that investigate wood quality in spruce roundwood by storage method.

Armillaria spp. are treated separately due to their recurring, storage-specific manifestation patterns under irrigated conditions, irrespective of their general decay classification. Characteristic symptoms such as rhizomorph networks, mycelial fans, and dark lines of demarcation were consistently documented on irrigated log piles where surface wetting and limited aeration created suitable growth conditions (). These studies applied field visual assessment, inoculation trials, and microscopic analysis to describe the spatial spread and oxygen supply mechanisms, including the formation of tubular air channels in water-saturated sapwood.

Other forms of decay were reported under dry or cold storage conditions. Hard rot, describing early decay stages where the woody texture remained intact, and soft rot, characterised by friable or fibrous structure and measurable dry-mass loss, were observed in stored logs. These user-oriented decay types were complemented by biologically defined brown-rot and white-rot mechanisms, caused by decay fungi such as *Armillaria mellea s.l., Coniophora puteana* (Schum.) P. Karst., *Gloeophyllum trabeum* (Pers.) Murill, or *Trametes versicolor* (L.) Lloyd. Assessment methods included visual sectioning, mass-loss determination, and fungal inoculation assays.

Non-decay fungal indicators such as blue-stain and red-streak fungi were assessed in context of stored logs. Blue-stain are the hyphae of a variety of fungi belonging mostly to the orders *Microascales* and *Ophiostomatales* (Kirisits 2004). They are commonly associated with insects, which are common in the forest and transfer fungal spores (Hartig 1844, Münch 1907, 1908, Kirisits 2004). Red-streak is caused by fungi belonging to the family *Corticiaceae* s. lat. *(Stereaceae* PILAT 1930*)* (Pechmann et al. 1967, Kleist 2001). For example, with *Stereum sanguinolentum* (Alb. et Schw.: Fr.) Fr. und *Amylostereum areolatum* (Chaill.: Fr.) Boid. there is evidence in the supporting literature for an association with wood-wasps belonging to the family *Siricidae* (Francke-Grosmann 1939).

Discolouration developed rapidly after felling, reducing wood brightness and surface quality. Quantification relied on

Table 2. Summary of biological quality indicators occurring in spruce roundwood during storage, showing the corresponding visible or measurable effects, assessment approaches, storage environments in which they were documented, and literature sources.

Quality indicator	Observable effect	Assessment method	Storage method	References
Armillaria spp.	Mycelial cords Lines of Demarcation Rhizomorphs Mycelial fans Discolouration	Visual assessment Inoculation Microscopic inspection	Wet storage – Sprinkling	(Metzler 1994, Groß and Metzler 1995, Schumacher and Grosser 1995, Groß *et al*. 1996, Webber and Gibbs 1996, Metzler and Hecht 2004, Stuhlmann *et al*. 2012)
Bacteria infestation	Smell Discolouration	Visual assessment Microscopic inspection Conclusion from chemical Composition	Bio-chemical treatment Foil storage Wet storage – Sprinkling Wet storage – Water storage	(Adolf *et al*. 1972, Aufsess *et al*. 1974, Bues 1986, Webber and Gibbs 1996, Maier 2005, Stuhlmann *et al*. 2012)
Blue-stain fungi	Sap-stain Discolouration	Visual assessment (cross section / Envelop surface / bore cores / Sawn timber) Microscopic inspection Inoculation	Bio-chemical treatment Cold storage Dry storage – Covered pile Dry storage – Uncovered pile Foil storage – Swiss method Foil storage – Baden-Württemberg method Wet storage – Sprinkling	(Aufsess *et al*. 1974, Göttsche-Kühn and Frühwald 1986, Groß and Lübbers 1992, Liukkoxs and Elowsson 1999, Yang *et al*. 1999, Yang and Rossignol 1999, Mäkelä *et al*. 2000, Mäkelä *et al*. 2001, Persson and Elowson 2001, Mäkelä and Achren 2003, Lind *et al*. 2004a, Maier 2005, Jonsson 2006, Morin *et al*. 2006, Beal *et al*. 2010, Dimou 2012, Rademacher and Hapla 2012, Jonsson 2012a, Böhm *et al*. 2023, Michalec *et al*. 2024, Böhm *et al*. 2025, Trautwein *et al*. 2026)
Red-streak fungi	Sap-stain Discolouration	Visual assessment (cross sections) Inoculation	Bio-chemical treatment Dry storage – Uncovered pile Foil storage – Swiss method Foil storage – Baden-Württemberg method Wet storage – Water storage	(Aufsess and Pechmann 1970, Göttsche-Kühn and Frühwald 1986, Groß *et al*. 1993, Maier 2005, Rademacher and Hapla 2012, Brischke and Wippermann 2022, Trautwein *et al*. 2025b, Trautwein *et al*. 2026, 2026)
Hard rot (phenomenological)	Decay (initial, woody texture intact)	Visual assessment (cross sections)	Cold storage Dry storage – Uncovered pile Foil storage – Swiss method	(Groß *et al*. 1993, Mäkelä *et al*. 2000, Mäkelä and Achren 2003, Michalec *et al*. 2024)
Soft rot (phenomenological)	Decay (friable, spongy, or fibrous) Mass loss	Visual assessment (cross sections)	Cold storage Dry storage – Covered pile Dry storage – Uncovered pile	(Mäkelä *et al*. 2000, Mäkelä and Achren 2003, Michalec *et al*. 2024)
White rot (biological)	Mycel growth Mass loss Decay Discolouration	Visual assessment (cross sections / envelop surface) inoculation	Bio-chemical treatment Foil storage – Baden-Württemberg method	(Metzler *et al*. 1993, Maier 2005, Brischke *et al*. 2020, 2021)
Brown rot (biological)	Mycel growth Mass loss Decay Discolouration	Visual assessment (cross sections / envelop surface) inoculation ergosterol content (see. Table 3)	Bio-chemical treatment Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling	(Metzler *et al*. 1993, Bjurman and Viitanen 1996, Maier 2005, Brischke *et al*. 2020, 2021)
Rot (no further description)	Decay	Visual assessment (envelop surface / face ends)	Foil storage – Swiss method	(Rademacher and Hapla 2012)
Fungal decay (no further description)		Visual assessment (lumber surface) Pick test acc. to EN 252:2015-01 (lumber surface)	Dry storage – Covered pile	(Trautwein *et al*. 2026)
Fungi (no further description)	Surface mycelium No internal rot	Visual assessment (envelop surface / face ends)	Foil storage – Swiss method	(Rademacher *et al*. 2011)
Insect infestation	Boreholes Galleries Frass	Visual assessment (envelop surface) Boring trace count	Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Wet storage – Sprinkling	(Webber and Gibbs 1996, Maier 2005, Böhm *et al*. 2025, Trautwein *et al*. 2026)
Mould fungi	Mould	Visual assessment Microscopic inspection Mycologic assessment	Wet storage – Sprinkling	(Webber and Gibbs 1996, Riguelle *et al*. 2017)

visual assessment and delineation of cross-sections and envelope surfaces, occasionally supported by microscopic confirmation or inoculation. Bacterial activity and mould fungi were confined mainly to wet and foil storage, producing surface discolouration and fermentation-like odour. These were recorded visually or by microscopic and chemical analyses, including indicators of bacterial metabolism.

Across all studies, observable effects including mycelial development, discolouration, mass loss, odour, and insect damage were paired with quantitative and qualitative assessment methods such as visual assessment, inoculation, microscopy, or chemical and gravimetric analyses. These results delineate the full range of biotic influences on spruce log quality across wet, dry, cold, foil, live, ground, standing and bio-chemical storage types, establishing a consistent empirical basis for subsequent categorisation of storage-related quality indicators.

3.2.2. Chemical quality indicators

Chemical quality indicators describe changes in the chemical composition and microchemical state of spruce roundwood during storage and were addressed in a number of the reviewed studies. Table 3 summarises the chemical quality indicators identified in the reviewed studies, together with their observable or measurable effects, applied analytical methods, storage environments, and corresponding references.

Explicit assessments of chemical quality indicators focused on both structural wood components and non-structural constituents. Across the reviewed literature the sugar composition (cellulose, hemicelluloses, holocellulose, starch) lignin, extractives, phenolic compounds, organic acids, and tannins were analysed, together with enzyme activity, microchemical transformation processes, and pH as integrative indicators of chemical degradation and microbial activity.

Alterations in carbohydrate composition were assessed primarily through sugar and holocellulose analyses. Structural polysaccharides were investigated as baseline indicators of chemical wood quality, while storage-related changes in sugar composition were quantified using chromatographic methods,

Table 3. Summary of chemical quality indicators occurring in spruce roundwood during storage, showing the corresponding visible or measurable effects, assessment approaches, storage environments in which they were documented, and literature sources.

Quality indicator	Observable effect	Assessment method	Storage method	References
Enzyme activity	Oxygen consumption Oxidation-Discolouration	UV/VIS-Spectroscopy	Dry storage – Covered pile Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Wet storage – Sprinkling	(Winter 2009)
Ergosterol content (proxy for *Coniophora puteana*)		HPLC	Wet storage – Sprinkling	(Bjurman and Viitanen 1996)
Ethanol content		Photometric UV-test	Bio-chemical treatment Foil storage	(Maier 2005)
Extractives content	Brightness	ASTM D1107-96 and Ånäs *et al.* (1983, as cited in Čabalová *et al.* 2021)	Dry storage – Uncovered pile Wet storage – Water storage	(Dahm 1966, Fengel and Wegener 1988, Čabalová *et al.* 2021, Hrčka *et al.* 2022, Čabalová *et al.* 2023)
Lignin content		HPLC GC Sluiter *et al.* (2012, as cited in Čabalová *et al.* 2021)	Dry storage – Uncovered pile Dry storage – Covered pile Foil storage – Baden-Württemberg method Wet storage – Sprinkling Wet storage – Water storage	(Fengel and Wegener 1988, Winter 2009, Čabalová *et al.* 2021, Hrčka *et al.* 2022, Čabalová *et al.* 2023)
Lipophilic compounds		GC	Dry storage – Covered pile Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Wet storage – Sprinkling	(Winter 2009)
Metal concentration (Ca, Fe, Mn)	Brightness Bleachability	Energy dispersive x-ray fluorescence Atomic absorption spectroscopy	Dry storage – Uncovered pile Wet storage – Sprinkling	(Persson and Lindeberg 2001)
Nitrogen content		Kjeldahl method	Dry storage – Uncovered pile	(Beal *et al.* 2010)
Organic acid concentration		HPLC HPICE GC	Bio-chemical treatment Dry storage – Covered pile Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling	(Bues and Weber 1998, Maier 2005, Winter 2009, Čabalová 2025)
PH		pH metre	Dry storage – Uncovered pile Foil storage – Baden-Württemberg method	(Bues and Weber 1998, Čabalová *et al.* 2023, Čabalová 2025)
Phenolic compounds	Brightness Bleachability	UV-test Nutrient analysis (e.g. Sauvesty *et al* 1992, as cited in Beal *et al.* 2010)	Dry storage – Uncovered pile Wet storage – Water storage	(Loras 1974, Beal *et al.* 2010)
Sugar composition		HPLC Sugar analysis (e.g. acc. to Ward and Deans (1993, as cited in Beal *et al.* 2010) or Seifert (1956, as cited in Čabalová et al. 2021 and Wise *et al.* (1946, as cited in Čabalová *et al.* 2021))	Bio-chemical treatment Dry storage – Uncovered pile Dry storage – Covered pile Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkled Wet storage – Water storage	(Fengel and Wegener 1988, Bues and Weber 1998, Winter 2009, Beal *et al.* 2010, Čabalová *et al.* 2021, Hrčka *et al.* 2022, Čabalová *et al.* 2023)
Tannin impregnation/ tannin leaching	Discolouration Brightness	Visual assessment (Fluorescence) microscopy	Dry storage – Uncovered pile Wet storage – Sprinkling	(Groß and Lübbers 1992, Persson and Elowson 2001, Jonsson 2004, Hildén *et al.* 2006)

including high-performance liquid chromatography (HPLC), high-performance ion-exclusion chromatography (HPICE), and gas chromatography (GC). These approaches were applied under dry, foil, wet, and biochemical storage conditions to characterise hydrolytic and oxidative degradation processes affecting cellulose and hemicelluloses during prolonged storage.

Non-structural extractives and phenolic compounds were mainly examined in relation to optical wood properties. Extractives content was determined using standardised solvent-extraction methods and related analytical procedures, and changes were linked to brightness loss and discolouration under dry and wet storage conditions. Phenolic compounds and tannins were analysed using photometric UV tests, nutrient analyses, and microscopy-based approaches, including fluorescence microscopy, to explain chemically driven discolouration and reduced bleachability in dry and wet-stored logs.

Several chemical indicators served as proxies for biological activity. Ergosterol content, quantified by HPLC, was applied as an indirect indicator of fungal biomass and susceptibility of wet-stored logs to brown-rot fungi. Nitrogen content was analysed using the Kjeldahl-method to characterise nutrient availability and potential microbial activity in dry-stored and partially debarked logs. Enzyme activity, expressed through oxygen consumption and oxidation-related discolouration, was assessed using UV/VIS-Spectroscopy as a marker of ongoing biochemical reactions under dry, foil, and wet storage conditions.

Indicators associated with anaerobic or fermentation-related processes were reported mainly for foil storage and biochemical treatments. Ethanol concentrations were measured using photometric UV tests, while organic acid profiles were quantified using HPLC, HPICE, and GC. These indicators reflect microbial metabolism under oxygen-limited conditions and changes in the chemical environment of stored wood. Shifts in pH were measured using pH electrodes as integrative indicators of chemical and microbial processes, particularly under foil storage and dry storage conditions.

Inorganic constituents were considered in a small number of studies. Metal concentrations, including calcium, iron, and manganese, were analysed using energy-dispersive X-ray fluorescence and atomic absorption spectroscopy and were linked to brightness and bleachability under dry storage and sprinkled wet storage conditions.

Overall, chemical quality indicators complement biological and physical indicators by capturing underlying transformation processes that precede or accompany visible degradation, thereby contributing to a comprehensive assessment of spruce roundwood quality during storage.

3.2.3. Physical quality indicators

Physical quality indicators describe changes in the moisture state, mass, structure, geometry, and mechanical performance of spruce roundwood during storage and directly determine its technical usability (Table 4). In contrast to biological and chemical indicators, physical quality indicators capture both reversible condition-related effects, such as moisture content, and irreversible damage affecting mechanical integrity and processing behaviour.

Moisture content was the most frequently assessed physical indicator, reflecting its relevance for biological activity, drying behaviour, and weight-based log valuation. It was determined either on a dry-mass basis (MCd) or a fresh-mass basis (MCf), using gravimetric and electrical resistance methods, occasionally complemented by discrete or continuous weighing to achieve time series. In addition, one study (Beal *et al*. 2010) expressed moisture content relative to the fully saturated state (MCsat), reporting water content as a proportion of the maximum saturation capacity rather than on a fresh- or dry-mass basis. In one reference (Groß and Lübbers 1992), the basis of moisture content is not apparent due to the abbreviated nature of the contribution. From the context and the German term “Holzfeuchte”, it can be assumed that moisture content on a dry-mass basis (MCd) is meant.

Mechanical performance indicators included bending strength, compression strength, bark–wood shear strength, modulus of elasticity (MOE), and work to fracture in bending. Strength properties were assessed using standardised mechanical tests (DIN 52185, DIN 52186) and quantified maximum load-bearing capacity under different storage conditions. In contrast, work to fracture in bending (DIN 52189) represents an energy-based toughness parameter describing deformation and fracture behaviour and was therefore treated as a distinct indicator rather than a strength measure.

The MOE was determined both statically (three- or four-point bending) and dynamically using the Impulse Excitation Technique (IET, GRINDO SONIC). Dynamic MOE reflects small-strain elastic behaviour and is systematically higher than static MOE due to the exclusion of time-dependent deformation. The non-destructive character of IET enabled repeated measurements and was particularly suited for monitoring storage-related stiffness changes.

Indicators of physical integrity and dimensional stability included cracks and checks, curvature, twisting, and drying kinetics. Cracks and checks were widely used visual proxies for mechanical integrity across dry, wet, cold, and foil storage systems. Dimensional changes and drying behaviour were quantified using optical scanning techniques and controlled drying or soaking experiments, primarily to assess post-storage processing performance.

Density and mass loss functioned as integrative indicators of structural degradation. Density was determined using mass-to-volume ratios and immersion methods across most storage types, often in combination with visual decay assessments. Gravimetric mass-loss tests were applied mainly under dry, foil, and wet storage conditions to quantify biologically induced material loss, although density changes may also reflect moisture change or extractive loss.

Additional physical indicators related to transport properties and morphology included permeability, soaking capacity, fibre length and fibre width. Permeability and soaking capacity were assessed primarily under wet storage conditions using permeameter measurements, stain tests, and vacuum–pressure water uptake. Fibre dimensions, determined by automated fibre analysis systems, revealed storage-related reductions in fibre length and width, which are particularly relevant for pulp and paper applications.

Overall, physical quality indicators encompass both technical damages, affecting strength, stiffness, fracture behaviour, and permeability, and surface- or geometry-related changes,

Table 4. Summary of physical quality indicators occurring in spruce roundwood during storage, showing the corresponding visible or measurable effects, assessment approaches, storage environments in which they were documented, and literature sources.

Quality indicator	Observable effect	Assessment method	Storage method	References
Bending strength (static / dynamic)		DIN 52186 Four point bending test	Dry storage – Uncovered pile Foil storage – Baden – Württemberg method Wet storage – Water storage	(Adolf *et al.* 1972, Bues 1986, Göttsche-Kühn and Frühwald 1986, Bues and Weber 1998, Riguelle *et al.* 2017)
Compression strength (parallel to grain / in direction with the fibre)		DIN 52185	Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling Wet storage – Water storage	(Adolf *et al.* 1972, Bues 1986, Göttsche-Kühn and Frühwald 1986, Bjurman and Viitanen 1996, Rademacher and Hapla 2012)
Cracks / checks (proxy for good physical preservation / mechanical integrity)		Visual assessment (envelop surface / face ends)	Bio-chemical treatment Cold storage Dry storage – Covered pile Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Wet storage – Sprinkling Wet storage – Water storage	(Aufsess and Pechmann 1970, Aufsess *et al.* 1974, Steffen *et al.* 1995b, Mäkelä *et al.* 2000, Maier 2005, Stuhlmann *et al.* 2012, Riguelle *et al.* 2017, Michalec *et al.* 2024)
Density	Decay Rot	Mass to volume ratio Immersion method	Cold storage Dry storage – Uncovered pile Dry storage – Covered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling Wet storage – Water storage	(Adolf *et al.* 1972, Bues 1986, Göttsche-Kühn and Frühwald 1986, Bjurman and Viitanen 1996, Bues and Weber 1998, Mäkelä *et al.* 2000, Lind *et al.* 2004a, Lind *et al.* 2004b, Rademacher *et al.* 2011, Rademacher and Hapla 2012, Riguelle *et al.* 2017, Hrčka *et al.* 2022, Böhm *et al.* 2023, Čabalová *et al.* 2023)
Dimensional stability	Broadside curvature Narrow side curvature Twisting	FRITS ("Freiburg's Improved Timber Scan")	Dry storage – Covered pile Dry storage – Uncovered pile	(Klaiber and Seeling 2002)
Drying kinetics		Oven dry method	Dry storage – Uncovered pile Wet storage – Sprinkling	(Liukkoxs and Elowsson 1999)
Drying properties		Drying and soaking experiments under controlled conditions	Wet storage – Water storage	(Bues 1986)
Modulus of elasticity		Three point bending test Four point bending test Impulse Excitation Technique (IET) GRINDO SONIC	Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling Wet storage – Water storage	(Adolf *et al.* 1972, Göttsche-Kühn and Frühwald 1986, Webber and Gibbs 1996, Rademacher and Hapla 2012, Riguelle *et al.* 2017)
Fibre length		L & W Fiber Tester	Wet storage – Sprinkling Dry storage – Uncovered pile	(Lind *et al.* 2004a, Čabalová *et al.* 2021, Čabalová *et al.* 2023, Čabalová 2025)
Fibre width		L & W Fiber Tester	Wet storage – Sprinkling Dry storage – Uncovered pile	(Lind *et al.* 2004a, Čabalová *et al.* 2021, Čabalová *et al.* 2023, Čabalová 2025)
Impregnability			Foil storage – Baden-Württemberg method	(Riguelle *et al.* 2017)
Mass loss	Decay	Gravimetric mass-loss test	Dry storage – Covered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling	(Bjurman and Viitanen 1996, Brischke *et al.* 2020, 2021, Hrčka *et al.* 2022)
Moisture content (dry weight based)		Electric resistence method Oven dry method	Bio-chemical treatment Dry storage – Uncovered pile Dry storage – Covered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling Wet storage – Water storage;	(Aufsess and Pechmann 1970, Adolf *et al.* 1972, Aufsess *et al.* 1974, Bues 1986, Göttsche-Kühn and Frühwald 1986, Groß and Lübbers 1992, Groß *et al.* 1993, Webber and Gibbs 1996, Bues and Weber 1998, Metzler and Hecht 2004, Maier 2005, Nicholls and Brackley 2009, Winter 2009, Rademacher *et al.* 2011, Rademacher and Hapla 2012, Stuhlmann *et al.* 2012, Brischke *et al.* 2020, Hrčka *et al.* 2022, Trautwein *et al.* 2026)
Moisture content (fresh weight based)		Oven dry method Discrete weighing Continuous weighing	Cold storage Dry storage – Covered pile Dry storage – Uncovered pile Dry storage – debarked Dry storage – partly debarked Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Sprinkling	(Bjurman and Viitanen 1996, Liukkoxs and Elowsson 1999, Mäkelä *et al.* 2000, Mäkelä *et al.* 2001, Persson and Elowson 2001, Klaiber and Seeling 2002, Persson *et al.* 2002, Jonsson 2004, Mäkelä 2004, Lind *et al.* 2004a, Lind *et al.* 2004b, Jonsson 2006, Röser *et al.* 2011, Murphy *et al.* 2012, Jonsson 2012a, Riguelle *et al.* 2017, Böhm *et al.* 2023, Čabalová *et al.* 2023, Böhm *et al.* 2025)

(*Continued*)

Table 4. Continued.

Quality indicator	Observable effect	Assessment method	Storage method	References
Moisture content relative to the fully saturated state		Oven dry method	Dry storage – Uncovered pile	(Beal *et al.* 2010)
Permeability		PMB permeameter Stain test	Wet storage – Sprinkling	(Adolf *et al.* 1972, Bjurman and Viitanen 1996)
Porosity			Wet storage – Sprinkling	(Webber and Gibbs 1996)
Soaking capacity (proxy for permeability)		Vacuum-pressure water uptake	Wet storage – Water storage	(Bues 1986)
Work to fracture in bending		DIN 52189	Bio-chemical treatment Dry storage – Uncovered pile Foil storage – Baden-Württemberg method Foil storage – Swiss method Wet storage – Water storage	(Adolf *et al.* 1972, Göttsche-Kühn and Frühwald 1986, Maier 2005, Rademacher and Hapla 2012)

such as cracking and deformation. Together, they provide a concise yet comprehensive framework for evaluating the physical consequences of different spruce roundwood storage strategies.

3.2.4. Grading systems as integrative quality assessment frameworks

In addition to the biological, chemical, and physical indicators described above, roundwood grading systems provide an operational framework for assessing wood quality in a market context. Systems such as the German RVR (Deutscher Forstwirtschaftsrat and Deutscher Holzwirtschaftsrat 2024) and the Austrian ÖHU (Fachverband der Holzindustrie Österreichs), as well as standardised measurement and classification frameworks applied by Biometria (2019) in Sweden, translate observable quality indicators into quality classes used for trade and processing. Comparable systems exist in other countries, reflecting region-specific market structures and industrial requirements. At the European standardisation level, standards such as (DIN EN 1927-1) provide general rules for the visual classification of softwood roundwood, but play a comparatively minor role in operational grading practice.

These grading approaches aggregate multiple visible attributes such as dimensions, form, and defects including discolouration, rot, or mechanical damage into simplified classes representing end-use suitability. As such, they constitute the practical interface between wood condition and economic value. However, grading systems are inherently outcome-based and rely on visually assessable features at the time of measurement. Regarding the reviewed literature, a number of studies reported on the assigned roundwood quality classes according to the RVR (Rademacher and Hapla 2012, Brischke and Wippermann 2022, Trautwein *et al.* 2025b, Trautwein *et al.* 2026) and quality classes of lumber (Rademacher and Hapla 2012, Trautwein *et al.* 2026).

3.3. Storage and its effects

3.3.1. Process conditions governing quality development during storage

Roundwood quality development is governed by storage conditions, which can be characterised by key process variables describing the storage environment. Key variables include oxygen availability (directly measured or inferred from carbon dioxide concentrations; e.g. Winter 2009, Rademacher *et al.* 2011, Rademacher and Hapla 2012, Brischke *et al.* 2020, 2021, Brischke and Wippermann 2022), temperature (e.g. Murphy *et al.* 2012, Böhm *et al.* 2023, Böhm *et al.* 2025, Trautwein *et al.* 2025b, Trautwein *et al.* 2026), and moisture availability (e.g. Beal *et al.* 2010, Murphy *et al.* 2012, Böhm *et al.* 2023). These variables jointly control biological activity and physico-chemical transformation processes in stored wood.

For example, oxygen depletion under airtight foil storage suppresses fungal and insect metabolism, while low temperatures in cold storage inhibit biological activity. Moisture availability, often expressed through derived variables such as equilibrium moisture content or vapour pressure deficit, regulates both fungal colonisation potential and drying dynamics.

These process conditions do not constitute quality indicators themselves but determine the rate and direction of quality change, thereby providing a mechanistic link between storage conditions and observable quality changes and grading outcomes.

3.3.2. Dry storage

Dry storage comprises roundwood storage systems without active humidification and includes both, uncovered piles exposed directly to ambient weather conditions and covered piles in which precipitation and solar radiation are partially excluded while air exchange remains largely unrestricted. Storage proceeds under aerobic conditions, permitting oxidative and microbial degradation. Covered piles may range from stacks protected only on the upper surface by tarpaulins to simple roof systems designed to accelerate drying, as well as storage in open-sided sheds or indoor facilities. These variants differ mainly in ventilation intensity and degree of environmental exposure, which govern temperature and moisture dynamics and, consequently, biological activity.

In addition to these basic storage variants, a range of technical measures and handling specifications can be applied within dry storage systems to mitigate wood quality deterioration. These include the use of support logs or sleepers to elevate log piles from the ground and reduce moisture uptake, as well as partial or complete debarking or bark gouging to limit bark beetle colonisation and associated fungal infection. Furthermore, pile geometry and formation, such as cross-layered stacking or increased spacing between logs, can enhance air circulation and promote more uniform drying. While these measures do not alter the fundamentally aerobic nature of dry storage, they can influence microclimatic conditions within the pile and thereby delay biological degradation processes.

Prolonged exposure under aerobic conditions leads to gradual physicochemical and biological changes in spruce wood. Wood extractives, including terpenes, fatty acids, and phenolic compounds, decline during storage through volatilisation, oxidation, and microbial metabolism (Winter 2009). These losses are influenced by storage conditions, with rates dependent on temperature and surface exposure, which affect drying behaviour and susceptibility to discolouration (Groß and Lübbers 1992, Winter 2009).

Chemical analyses revealed that calcium and iron concentrations declined in dry-stored spruce after three months, reflecting leaching and surface oxidation, whereas wet-stored logs accumulated manganese from irrigation water (Persson and Lindeberg 2001). Similar patterns of weathering-related element loss were observed by Göttsche-Kühn and Frühwald (1986) after yard storage in polluted areas of Germany.

Sirvio *et al*. (2012) further demonstrated that outdoor summer storage of spruce logs leads to chemical darkening and loss of pulp brightness in thermo-mechanical pulping. Increased formation of oxidised extractives required 8–10 kg more peroxide per BDt of pulp to reach roughly 75% ISO brightness compared with fresh wood, confirming substantial oxidative modification of the extractive fraction during dry storage.

Hemicellulose emerged as the most labile wood component, with relative losses increasing with storage duration, measured as saccharide content. By contrast, cellulose showed minimal change, while lignin content remained stable in both investigations. pH measurements confirmed acidification during storage, though organic acids (acetic and formic) were not detected in outdoor conditions, likely due to volatilisation (Čabalová *et al*. 2021, Čabalová *et al*. 2023).

Complementary spectroscopic and morphological analyses revealed progressive surface changes in air-dried spruce, together with gradual changes in lignin and extractive composition (Čabalová *et al*. 2021, Čabalová *et al*. 2023, Čabalová 2025). These findings align with earlier reports of colour alteration and metal leaching during extended exposure (Göttsche-Kühn and Frühwald 1986, Persson and Lindeberg 2001) and collectively indicate that oxidative, moisture-dependent processes govern the long-term degradation of spruce wood stored under dry, aerobic conditions, which could potentially reduce strength (Čabalová *et al*. 2023).

Moisture content evolution during storage follows distinct patterns depending on environmental exposure and protective measures. In unprotected dry storage, freshly felled spruce logs (initial sapwood moisture ~140-180% MCd, heartwood ~40-60% MCd) undergo progressive desorption (Klaiber *et al*. 2002, Klaiber and Seeling 2002, Nicholls and Brackley 2009). Sapwood in Sitka spruce (*Picea sitchensis* (Bong.) Carrière) contains approximately 3.5 times higher initial moisture content than heartwood (142% vs. 41% MCd) (Nicholls and Brackley 2009) and exhibits substantially higher permeability, resulting in different drying rates between sapwood and heartwood zones (Avramidis *et al*. 2023). Murphy *et al*. (2012) developed a predictive model for Sitka spruce in off-forest environment incorporating cumulative rainfall, evapotranspiration, initial moisture content and type of cover, achieving accurate drying rate predictions down to measured MCf values of 30%.

Hrčka *et al*. (2022) measured dry-matter losses of approximately 5–6% yr^{-1} (4.5% after six months of indoor storage) in air-dried spruce roundwood, attributed primarily to hemicellulose degradation. Röser *et al*. (2011) likewise observed a decrease in equilibrium moisture content and minor mechanical softening after up to 12 months of natural air-drying. However, there is evidence that unprotected wood storage for several months did not lead to significant reduction in mechanical properties (Göttsche-Kühn and Frühwald 1986), or adversely affected the dimensional stability (warp and twist) of the resulting sawn timber due to uncontrolled pre-drying during storage (Klaiber and Seeling 2002).

3.3.2.1. Unprotected piles and roadside storage. Roadside and open-yard storage are widespread because of their simplicity but rapidly lead to wood deterioration if storage extends into growing season. Studies on unprotected forest storage of spruce roundwood over several months document that discolouration from fungal activity occurs early (Göttsche-Kühn and Frühwald 1986). In Nordic studies, exposed top logs of spruce piles lost more than 1% moisture (MCf) per day during early summer, while shaded logs dried substantially slower (Persson *et al*. 2002). Under controlled exposure experiments, spruce generally exhibited lower sap-stain intensity than pine or larch, with first visible discolouration after approximately 4–6 weeks, confirming its comparatively moderate susceptibility among conifers (Beal *et al*. 2010). Fungal colonisation intensified once average moisture content dropped below roughly 50% (MCf).

Under central-alpine conditions, Böhm *et al*. (2023) demonstrated in log storage trials that blue-stain onset was delayed to 80–100 days in logs felled in March but occurred within two weeks in logs harvested in June. The proportion of stained area correlated strongly with cumulative temperature, confirming temperature as an important driver of biological degradation under dry storage. Moisture content had only a minor effect compared with thermal exposure. Earlier investigations under Nordic and Mediterranean conditions support this pattern. In Sweden, blue-stain appeared after approximately 8 weeks (Persson and Elowson 2001), while in northern Greece visible blue-stain and red-streaks developed within 10–14 days on freshly summer-felled spruce (Dimou 2012). Winter felling in Greece substantially restricts fungal infection, maintaining logs at minimal or zero infestation levels for several months (Dimou 2012). These findings demonstrate that climate, particularly temperature and exposure, determines the duration of safe dry storage, whereas initial moisture or bark condition are of secondary importance.

Similar patterns can be observed with decay fungi. Pulpwood remains fundamentally resistant to fungal rot colonisation during winter storage (November-April), but undergoes rapid and accelerating defect accumulation once temperatures rise in late spring (May onwards). This temperature-driven pattern is consistent across all tree species (spruce, pine, birch) and geographic regions studied (Finland, Estonia, Latvia) (Mäkelä *et al*. 2000).

3.3.2.2. Whole-tree and forest-side storage. Klaiber and Seeling (2002) analysed combined whole-tree and subsequent log-pile storage of spruce under natural drying conditions in Sauerland (Germany). Despite up to 155 days of whole-tree and 313 days of log storage in a pile, MCf decreased by about 18%, and no statistically significant differences were detected in the dimensional stability of the resulting kiln-dried timber. Average twist and bow values (approx. 2 cm / 2 m and 0.4–0.5 cm / 2 m, respectively) remained within normal variability. The authors concluded that pre-drying spruce roundwood in forest conditions provides no measurable advantage for later wood quality and may even risk biological degradation if extended into warm seasons.

3.3.2.3. Bark condition and debarking. Bark condition influences both drying rate and biological activity. Logs stored with intact bark retain higher moisture and experience less cracking, whereas debarked logs dry faster but are more susceptible to surface checking after 6–10 weeks (Jonsson 2012a).

Early Finnish observations already indicated that mechanical delimbing damage predisposes spruce logs to cracking and local blue-stain during subsequent short-term storage (Mäkelä and Pennanen 1980). Although not a controlled storage experiment, the findings support later reports on the role of bark and cambium integrity in determining storage performance. Bark remains adherent for 2–6 months post-harvest, with adhesion strength declining as cambial tissues dry and decompose. Logs intended for mechanical debarking benefit from 1–4 weeks of dry storage to reduce cambial moisture and bark adhesion, facilitating clean bark removal (Liukkoxs and Elowsson 1999).

Liukkoxs and Elowsson (1999) reported that spruce pulpwood with extensive bark damage (approx. 70% of bark removed) and an initial MCf of 52.0% dried markedly faster than logs with only minor bark loss (approx. 15% of bark removed) and an initial MCf of 54.8%. In the heavily damaged logs, outer-sapwood moisture content dropped below the critical 50% threshold, beyond which susceptibility to staining fungi and brightness loss increases, after approximately four weeks of dry storage. In contrast, the low-damage material required roughly eight weeks to reach the same level. Nicholls and Brackley (2009) examined outdoor vs. indoor air-drying of Sitka spruce logs in southeast Alaska, documenting that bark presence significantly influences drying rates, with debarked logs stored indoors showing the fastest drying.

Böhm *et al*. (2025) provided detailed insight into the effects of processor-debarking on spruce log quality under alpine conditions. In repeated trials, processor-debarked logs showed delayed blue-stain onset during the first few weeks of storage in comparison to bark-covered logs. Debarking significantly reduced blue-stain discolouration and led to fewer insect entry holes, particularly from *I. typographus* and *T. lineatum*. Similar tendencies have been observed in other climatic regions. In northern Greece, Dimou (2012) reported that debarked spruce logs developed significantly less blue-stain discolouration than bark-covered ones during the first 10–14 days after felling, although they also dried faster and exhibited more surface cracks. These observations underline that bark removal mitigates fungal colonisation across a wide climatic range but accelerates drying-related mechanical changes. However, for long-term storage exceeding half a year, the effect reversed, and more intensive blue-stain was found on the debarked logs (Böhm *et al*. 2025). Debarked logs also displayed more pronounced cracking, likely due to steeper moisture gradients during drying. These results show that debarking effectively limits fungal and insect colonisation in the short term but increases the risk of defects during extended dry storage.

Beyond wood-quality aspects, recent research has highlighted the pest-control and ecological implications of bark modification. It has been demonstrated that mechanical debarking reduces *I. typographus* breeding systems by 95–100% and nearly eliminates *T. lineatum* colonisation in southern Germany (Zarges *et al*. 2024). Comparable observations were made by Böhm *et al*. (2025) under alpine conditions. These results show, the efficacy of this measure, particularly when applied during peak insect flight periods. Thorn *et al*. (2016) and Zarges *et al*. (2023) further showed that partial bark scratching – a selective removal of outer bark – can suppress beetle emergence by 96–99.9% while maintaining habitats for saproxylic species, offering a practical compromise between economic and ecological objectives.

3.3.2.4. Covered piles and engineered dry conservation. Covering piles with tarpaulins or simple roofs moderates rainfall and UV exposure without restricting air exchange. These systems represent an intermediate stage between fully open and foil-sealed storage. If positioned on well-drained, ventilated ground, such coverings can stabilise moisture and reduce surface greying but do not prevent fungal colonisation once temperatures are within a range favourable for fungal activity.

Engineered dry conservation aims to accelerate drying below fungal tolerance thresholds while minimising cracking. German field trials in the 1990s established technical standards for conifers, including spruce (Anonymous 1995, Steffen *et al*. 1995a, 1995b). Fresh, healthy, preferably debarked logs were stacked as ventilated layered pile in sun-exposed yards. After 12 months, moisture content averaged 15–22% (MCd), surface checking was limited to $\leq$ 4 mm width and $\leq$ 7 cm depth, and blue-stain occurred on < 5% of surfaces. Bending and compression strengths remained unchanged compared with freshly sawn material. The process required no water-management permits and produced half-dry saw logs suitable for immediate processing. Reported total costs of approximately 20 DMm^{-3} (10.23 € m^{-3}, fixed euro conversion) including transportation, piling, material and maintenance (Steffen *et al*. 1995b), were about 10-50% lower than typical costs for wet storage. Key risk factors included unfavourable weather and poor pile ventilation; dense heap piles were discouraged because inner layers remained wet and susceptible to stain. Complementary studies in Finland confirmed similar behaviour of dry-stored spruce pulpwood: when covered and ventilated, quality remained stable through winter, but rapid summer drying caused checking and stain if surface moisture fell below 20% (MCf) (Mäkelä *et al*. 2000, Mäkelä 2004). While dry storage can maintain the usability of spruce roundwood over extended periods, quality losses due to fungal degradation, staining and insect infestation still occur, with damage often confined to the outer stem zones and strongly influenced by the initial moisture content of the logs (Trautwein *et al*. 2026).

3.3.3. Wet storage

While dry storage takes place under aerobic conditions that allow oxidative and microbial degradation, wet storage methods rely on the reduction or exclusion of oxygen to suppress such processes. Under these conditions, only a few facultative anaerobic microorganisms remain active, none of which significantly affect wood integrity (Aufsess *et al*. 1974, Bjurman and Viitanen 1996). This principle forms the basis of both wet and foil storage, in which oxygen depletion is achieved either through water saturation or airtight enclosure.

Fresh spruce wood is well suited for wet storage due to its moderate density, and low extractive content, which allow uniform moisture distribution and reduce leaching of organic compounds (Malan 2004, Jonsson 2012a). Compared with more resinous conifers such as pine, spruce is less susceptible to staining and bacterial degradation, while its low resin content limits environmental impacts from runoff. These characteristics make spruce particularly suitable for long-term wet storage, allowing effective preservation of wood quality with minimal biological or chemical deterioration.

3.3.3.1. Sprinkling. Wet storage by sprinkling is considered one of the most effective methods for preserving roundwood quality in Central Europe (Peek and Liese 1977, Anonymous 2002, Lind *et al*. 2004a, Anonymous 2006, 2019, 2020b). Evidence of its application to spruce wood in Germany dates back to the 1960s (Aufsess and Pechmann 1970, Aufsess *et al*. 1974). In this method, irrigation systems are installed in woodyards to maintain high moisture content by continuous or intermitted sprinkling log piles with water. Sustained moisture effectively prevents insect infestation and fungal colonisation. Under dry storage conditions, blue-stain developed within approximately eight weeks, whereas sprinkling effectively prevented its occurrence However, sprinkled logs showed increased brown surface discolouration from iron and tannin reactions (Persson and Elowson 2001). In Addition, sprinkling prevents surface checking and crack formation and thereby preserves mechanical strength (Aufsess *et al*. 1974, Webber and Gibbs 1996, Jonsson 2004).

Sprinkling maintains logs at or above fibre saturation (typically 145-180% MCd in sapwood, 35-50% MCd in heartwood (Webber and Gibbs 1996)), effectively preventing moisture loss and associated shrinkage below the fibre saturation (Aufsess *et al*. 1974, Jonsson 2004). Webber and Gibbs (1996) reported that continuous irrigation, operated almost 24 h per day, maintained very high moisture contents in Sitka and Norway spruce logs for various storage periods ranging from 6–36 months, effectively preventing fungal stain and most storage-related degrade.

Liukkonen and Elowsson [53] demonstrated that climate-adapted sprinkling can stabilise or even increase the moisture content of spruce logs only when applied before moisture content drops below approximately 50% (MCf). Logs entering wet storage within two to four weeks after felling maintained moisture contents close to 60% and showed a more homogeneous moisture distribution, confirming the importance of early transfer to wet storage. Once MCf had fallen below about 50%, subsequent climate-controlled wet storage did not meaningfully increase moisture content, indicating that reduced permeability had already limited rewetting.

Aufsess and Pechmann (Aufsess *et al*. 1974) showed that the moisture content of sprinkled wood stored for two years remained consistently high and occasionally exceeded 200% (MCd), comparable to that of wood stored fully submerged in water (Aufsess and Pechmann 1970). Superficial discolouration from tannin impregnation or blue stain typically penetrated only up to 20 mm into the sapwood and did not affect the value of sawn timber, as these outer sections are usually removed as slabs or chips during sawing (Aufsess *et al*. 1974).

Groß and Lübbers (1992) reported, that when irrigation ceased and the wood began to dry, discolouration due to tannin leaching occurred within two days, and blue-stain fungi developed within approximately 15 days (Groß and Lübbers 1992). Hildén *et al*. (2006) showed that bark-derived tannins during wet storage accumulate preferentially on pit membranes rather than throughout cell interiors, suggesting spatially limited discolouration. Decay caused by the brown-rot fungus *C. puteana* was delayed in previously wet-stored wood, as indicated by lower ergosterol concentrations and reduced mass loss likely due to reduced availability of non-structural carbohydrates and moisture-related limitations to gas exchange (Bjurman and Viitanen 1996).

A fermentation-like odour, attributed to bacterial activity, was reported from sprinkled piles, and timber sawn from wet-stored logs reportedly exhibited faster drying than freshly cut wood (Aufsess *et al*. 1974). A possible explanation could be increased permeability caused by bacterial degradation of the bordered pit membranes (Bjurman and Viitanen 1996).

Periodic inspections of sprinkled spruce wood indicated that colonisation by *Armillaria* spp. may occur after approximately three years of storage (Metzler 1994, Groß and Metzler 1995, Groß *et al*. 1996). Similar findings from a survey of 42 storage sites in Bavaria suggested that *Armillaria* spp. infestation typically develops after four years (Schumacher and Grosser 1995). The damage was confined to the sapwood, primarily affecting bark-covered logs in the inner sections of piles located below elevations of 1000 m a.s.l. Nevertheless, only a minor proportion of wet-stored logs were reportedly considered damaged by buyers (Groß and Metzler 1995, Groß *et al*. 1996). Fungal penetration remained confined to the sapwood and showed considerable spatial variability, whereas reductions in mechanical strength occurred only in strongly discoloured and decayed sections (Schumacher and Grosser 1995).

The ability of *Armillaria* spp. to colonise highly water-saturated sapwood (moisture content >150% MCd) has been attributed to the formation of tubular air channels that connect to the outer surface, facilitating oxygen diffusion several centimetres into the wood (Metzler 1994, Metzler and Hecht 2004). This structural adaptation enables the fungi to maintain aerobic metabolism and degrade wood tissues even under waterlogged conditions (Metzler and Hecht 2004). The reviewed literature further suggests that water quality may influence the occurrence of *Armillaria* spp. colonisation, although this assumption is based on professional observations rather than controlled experimental evidence (Anonymous 2002, Oberkobler 2002).

Wet storage by continuous sprinkling is associated with high technical complexity and significant water demand, particularly in industrial log yards where large timber volumes are maintained over extended storage periods (Jonsson 2004). Excess irrigation increases operational costs and may promote bacterial activity and tannin leaching, whereas adaptive, weather-controlled systems reduce water use by up to 70% (Lind *et al*. 2004a, Lind *et al*. 2004b, Anonymous 2019).

Runoff from wet storage typically contains organic carbon, phenols, and nutrients, posing risks of oxygen depletion and eutrophication (Jonsson 2004, Jonsson 2012a). Pollutant release can be mitigated through debarking, closed water recirculation, or vegetated filter systems, which remove up to 95% of organic carbon and phosphorus (Jonsson 2004, Jonsson 2006, Jonsson *et al*. 2006). Modular installations with integrated filtration and climate-responsive irrigation enable rapid deployment after disturbance events and minimise external water use. Estimated costs range from 18 to 26 € per m^3 for 24 months of operation (Stuhlmann *et al*. 2012). Experiences from Germany and Britain demonstrate that wet storage is technically effective but economically and environmentally feasible only at accessible, large-scale sites with reliable water resources and coordinated management (Webber and Gibbs 1996, Anonymous 2020b).

3.3.3.2. Water storage. With only five, there were substantially less studies found, which evaluated the quality of spruce roundwood that was stored submerged in a body of water (Aufsess and Pechmann 1970, Adolf *et al*. 1972, Loras 1974, Bues 1986, Fengel and Wegener 1988).

In one of the referred cases (Aufsess and Pechmann 1970), between 80 and 100 stems were tied to single-layer rafts to facilitate management and maintenance in the pond. The unintended multi-layering of stems that were not tied to rafts, but were instead left to float freely, caused some stems to be insufficiently submerged. This rendered the quality-preserving potential of the wet storage ineffective for these stems. Spruce wood that had been sufficiently submerged for two years showed no signs of deterioration due to fungal attacks. Furthermore, there were no cracks or insect infestations and structural integrity was preserved. Investigations showed that the previously wet-stored wood was more susceptible to fungal infection during subsequent natural drying in the forest, than freshly felled wood. More blue-stain and red-streak discolouration was observed. However, it should be noted that fungal infection that took place prior to the wet storage could not be ruled out (Aufsess and Pechmann 1970).

Bues (1986) tested properties of spruce wood that was forgotten in a pond for 17 years. Discolouration on the cross-sections and the stem surface reached only a few millimetres into the wood. The compression and bending strengths of the wood decreased by 20% and 6%, respectively, compared to freshly cut spruce wood of a similar raw density. However, it should be noted that the measured values from the freshly cut wood were considerably higher than common mean values, according to DIN 68364. This is in line with results from Efransjah *et al*. (1989), who reported minimal changes in MOE and bending strength when moisture levels are sufficiently maintained during storage periods of several months. Similar trends were observed by Adolf *et al*. (1972), who reported that spruce wood subjected to three years of water storage remained largely free of visible degradation, while mechanical properties were only moderately reduced (approximately 10–15%), with changes primarily confined to the outer sapwood.

Chemical analysis of the 17 year pond stored wood revealed that the sugar composition was not altered greatly with cellulose and hemicellulose content remaining largely unchanged and the lignin degradation was about 6% (Fengel and Wegener 1988). The material exhibited improved permeability (enhanced drying and impregnation properties) attributable to bacterial action, yet this functional modification occurred without detectable degradation of cell wall polysaccharides and mechanical strength properties remained within the natural variation range of fresh forest wood.

The moisture content was similar to that of freshly felled spruce timber. There was also evidence that small parts of bark-covered stems reaching out of the water did not dry out (Aufsess and Pechmann 1970). Spruce sapwood that has been stored in water shows increased drying and soaking rates compared to freshly cut wood. One possible explanation for this is that diffusion through the bordered pits is easier due to increased bacterial degradation (Aufsess and Pechmann 1970, Adolf *et al*. 1972, Bues 1986).

3.3.4. Foil storage

Following the severe storm events *Vivian* and *Wiebke* (1990), which caused extensive damage across Central Europe, particularly in Germany, alternative methods for the interim storage of spruce roundwood were evaluated in the early 1990s. In addition to purely chemical treatments such as face-end sealing with various substances, the covering of log piles with polyethylene foil was tested (Groß *et al*. 1993).

In contrast to water-based systems, foil storage achieves similar anaerobic conditions through airtight encapsulation rather than continuous irrigation or submersion. Experimental studies have shown that when oxygen levels within the storage environment fall below approximately 2%, fungal and insect metabolism ceases, while carbon dioxide accumulation from microbial and wood respiration stabilises the low-oxygen atmosphere (Metzler *et al*. 1993, Maier 2005, Riguelle *et al*. 2017).

Two design variants became established: (1) the Baden-Württemberg method, featuring a fully enclosed system with a ground foil, and (2) the Swiss method, in which the pile remains open toward the soil. Only the sealed Baden-Württemberg design maintained stable anaerobic conditions and effectively suppressed degrading fungi (Metzler *et al*. 1993, Maier 2005, Geibler and Scholz 2008, Rademacher *et al*. 2011, Rademacher and Hapla 2012, Brischke *et al*. 2020, 2021).

Early trials, testing the Swiss method, examined the development of wood moisture content and discolouration caused by blue-stain and red-streak fungi (Groß *et al*. 1993). Although the foil covering maintained a high moisture content (approx. 130% MCd), disadvantages were observed with respect to discolouration and decay. In piles that were not chemically treated, the wood moisture content even increased, indicating enhanced exchange processes between the wood and the surrounding atmosphere under the foil cover. As no foil layer was placed between the ground and the pile, additional moisture may have emerged from the soil into the covered pile.

In the experiments by Metzler *et al*. (1993), the use of a bottom foil combined with generous overlap of the cover foil created an almost gas-tight enclosure that effectively maintained the internal pile atmosphere. The test piles were gassed with either CO_2 or N_2, while one pile was wrapped in foil without gassing and another was stored without foil. Additionally, freshly cut spruce logs served as a control. Measurements showed that the oxygen concentration within the gassed piles declined to between 0.8 and 7.8%, while the wood moisture content remained high (up to 154% MCd). The treatment with CO_2 resulted in the lowest oxygen levels and was associated with the lowest fungal activity, confirming the effectiveness of low-oxygen storage under foil.

Later studies demonstrated that similar anaerobic conditions could be achieved without active gassing. Double-sealed PE-foil constructions led to rapid oxygen depletion due to microbial and wood respiration, accompanied by CO_2 accumulation (Bues and Weber 1998, Schüler and Wurster 2001, Maier *et al*. 2002, Maier 2005). Living parenchyma cells in freshly cut or storm felled wood use up the residual oxygen in a foil covered pile and reduce it down to a level that is sufficient to prevent fungal activity (Brischke and Wippermann 2022).

Long-term investigations confirmed that anaerobic storage has no negative impact on the physical or mechanical wood properties. Maier (2005) found that anaerobic conditions prevented fungal and bacterial cell wall degradation, maintaining original cellular architecture. However, instances of inadequate O_2 exclusion in beetle-killed wood with compromised bark permitted oxygen-tolerant fungi (i.e. *T. versicolor*) to degrade wood, though the specific degradation mechanisms at the cell wall level were not examined (Brischke *et al*. 2020). Riguelle *et al*. (2017) reported stable oxygen concentrations below 1% and CO_2 around 15% after 57 months of storage. MOE, static bending strength (MOR), impact bending strength and colour remained comparable to freshly cut reference logs, while surface moulds were restricted to the bark. Under these conditions, spruce wood could be preserved for several years without measurable quality loss (Riguelle *et al*. 2017). Similarly, Rademacher and Hapla (2012) reported well-preserved mechanical properties in logs stored under foil for approximately 30 months. Moreover, moisture dynamics is clearly reduced. Fresh sapwood (typically 140-180% MCd or higher) and heartwood maintaining high moisture content without external drying stress, thereby avoiding checking while preserving processing suitability (Maier 2005). Furthermore, properly executed foil storage under low oxygen atmosphere prevents mass loss (Bues and Weber 1998). This was confirmed by Riguelle *et al*. (2017), who reported no significant density changes in anaerobically stored spruce logs over 57 months.

Practical experience from operational applications further substantiated the method's reliability. Monitoring of foil-covered piles in Lower Saxony revealed oxygen depletion to nearly 0% within days and CO_2 accumulation up to 56% within months, with wood quality remaining within good B/C sawlog quality grades according to the framework agreement for the raw timber trade in Germany (RVR) (Deutscher Forstwirtschaftsrat and Deutscher Holzwirtschaftsrat 2024) even after several years of storage (Brischke and Wippermann 2022). However, quality losses occurred where the foil was damaged, emphasising the importance of airtightness. Similar results were reported from long-term trials in North Rhine-Westphalia, where spruce wood stored for up to five years under sealed foil retained structural quality suitable for construction (Anonymous 2020c, 2021, 2024).

In parallel, fumigation approaches have been evaluated to combine conservation and pest control. Hnatek *et al*. (2021) tested Ethanedinitrile (EDN) fumigation of spruce logs under PE-foil and demonstrated that a bottom foil was crucial for maintaining sufficient gas retention and achieving effective concentration–time products. Without a ground layer, EDN concentrations declined up to fivefold faster, substantially reducing efficacy.

According to Mühlhausen (2008a, 2008b) the quality of piling plays a decisive role in the effectiveness of foil storage. Logs should be of uniform length, straight, and free from protruding branches to allow dense stacking with minimal voids between them. A compact and stable pile reduces air pockets, ensures even microclimatic conditions, and prevents the ingress of oxygen, which is essential for maintaining an anaerobic environment under the foil. Proper pile formation thus enhances the preservation effect, reduces the risk of fungal colonisation, and contributes substantially to maintaining wood quality throughout the storage period.

From an operational perspective, the success of PE-foil storage depends primarily on airtight sealing, protection from mechanical damage, and regular monitoring of gas concentrations. The use of UV-stabilized multilayer foils and careful handling during pile formation are essential to prevent leaks that could lead to oxygen ingress and fungal growth (Brischke *et al*. 2020, Anonymous 2020a, Hauschild 2021, Brischke and Wippermann 2022). Recent evaluations report costs of 15 € to 20 € m^{-3} for the Baden-Württemberg method (Anonymous 2020a, Hauschild 2021). Economic analyses further suggest that cost parity with wet storage is achieved for storage periods exceeding approximately three years, due to the absence of continuous energy and water demand (Riguelle *et al*. 2017). Consequently, foil storage can represent a resource-efficient and environmentally compatible alternative for the interim preservation of spruce roundwood under Central European conditions.

3.3.5. Cold storage

In contrast to wet and foil storage, which preserve wood by creating anaerobic conditions that inhibit microbial activity, cold storage relies on physical temperature control to suppress degradation. By maintaining wood at or below the freezing point, biological and enzymatic processes are effectively halted, allowing spruce roundwood to be stored for several months without measurable deterioration (Mäkelä *et al*. 2001, Mäkelä 2002, Mäkelä and Achren 2003, Lukkari *et al*. 2004).

Cold storage has been developed primarily for Norway spruce in Finland, where it is applied to pulpwood and sawlogs harvested during winter. The method prevents thawing and preserves high wood moisture, thereby maintaining brightness, strength, and structural integrity until processing in summer or early autumn (Mäkelä and Achren 2003, Mäkelä 2004).

Two principal configurations are employed: (1) snow–sawdust insulation and (2) synthetic blanket systems. In the traditional snow–sawdust method, freshly felled spruce logs are piled compactly on well-drained ground and covered with a thick snow layer (0.6–1 m) insulated by 20–40 cm of sawdust, bark, or wood chips (Mäkelä *et al*. 2001, Mäkelä 2002, Mäkelä and Achren 2003). Some operations insert a geotextile or mesh fabric between snow and sawdust to stabilise the cover (Mäkelä *et al*. 2001). Piling is typically carried out from mid-December to early April, and piles are opened between July and October when processing capacity becomes available. Temperature measurements showed that the pile core remained close to 0 °C throughout storage, with only marginal warming in the outer layers during late summer (Mäkelä *et al*. 2001, Mäkelä and Achren 2003).

The blanket-based variant replaces the sawdust layer with reusable polyester-insulated PVC covers or low-emissivity membranes (Mäkelä 2002, Mäkelä and Achren 2003, Mäkelä 2004). These covers reduce snow melt and simplify handling while maintaining equivalent thermal performance. Field trials demonstrated similar temperature stability and 20–30% lower labour demand compared with sawdust insulation (Mäkelä 2002).

Extensive mill-yard trials comprising approximately 170 000 m^3 of winter-felled spruce pulpwood showed that cold-stored piles maintained high moisture content and exhibited negligible fungal or insect activity for up to ten months (Mäkelä *et al*. 2001, Mäkelä 2002, Mäkelä and Achren 2003). Log surfaces remained bright, end-checking was rare, and no blue-stain or decay fungi were detected where storage temperatures stayed below 2 °C. Physical and mechanical properties, including bending strength and density, were equivalent to those of freshly felled wood (Mäkelä 2004). In contrast, piles exposed to repeated freeze–thaw cycles developed superficial staining and shallow surface checks, emphasising the importance of continuous insulation and avoiding premature cover removal (Lukkari *et al*. 2004).

Cold storage is most effective for spruce logs harvested in mid-winter and requires rapid extraction and piling before sustained thawing (Mäkelä 2002, Mäkelä and Achren 2003). Piles should be compact, well-drained, and protected from wind to retain snow cover and minimise heat exchange (Mäkelä and Pennanen 1980).

On average, the snow–sawdust method uses about 0.27 m^3 of sawdust for every m^3 of stored spruce (Mäkelä 2004). In a representative case of a 35 000 m^3 spruce yard, total annual costs were estimated at approx. 59 000 €, corresponding to approx. 1.7 € m^{-3}. Of this, sawdust procurement and handling accounted for roughly 45%, labour for 35%, and fabric installation and removal for 20%. If sawdust is available as a by-product on-site, costs decrease to 1.3 € m^{-3}; if purchased externally, costs rise to 2 € m^{-3} (Mäkelä 2004).

Insulated synthetic blankets entail higher capital expenditure but lower operating costs. Initial investment for durable PVC–polyester covers is around 8–10 € m^{-2} of cover area, corresponding to roughly 1.8–2.2 € m^{-3} of stored wood in the first year. Assuming a five-year service life with reuse, annualised costs fall to 1.0–1.2 € m^{-3} (Mäkelä 2002), whereby transportation costs are not included. Blanket systems further reduce snow-removal labour and allow faster seasonal setup, offering advantages in large mechanised yards. Practical guidance emphasises maintaining intact cover integrity, ensuring full insulation continuity, and scheduling pile opening to coincide with mill intake in late summer (Mäkelä 2002, Lukkari *et al*. 2004, Mäkelä 2004).

3.3.6. Bio-chemical treatments

In addition to physical storage techniques, various chemical and biological approaches to inhibit fungal and bacterial degradation of spruce roundwood have been investigated. Early field trials examined face-end sealing and surface treatments with fungicidal formulations; however, these methods were of limited duration and raised environmental concerns regarding toxicity and durability (Groß *et al*. 1993). Subsequent research therefore focused on alternative, less toxic or biological measures that could complement or substitute conventional storage methods.

Under operational conditions, *Gliocladium roseum* Bainier (syn. *Trichoderma harzianum* Rifai) reduced sap-stain intensity on freshly cut *Picea mariana* (Mill.) Britton *et al*. and *P. glauca* logs by approximately 50% after four months of summer storage, but showed no protection against decay fungi and reduced efficacy on pre-colonised substrates, underscoring the importance of early and uniform application (Yang and Rossignol 1999). An albino strain named "Kasper" of *Ceratocystis resinifera* (syn. *Endoconidiophora resinifera* (T.C. Harr. & M.J. Wingf.) Z.W. de Beer) achieved comparable or higher efficacy in multiple field and mill-yard trials, reducing sap-stain incidence by 55–95% when applied within 24 h of felling (Morin *et al*. 2006). The protective mechanism relies on competitive substrate colonisation of freshly exposed sapwood, thereby excluding staining fungi without causing discolouration or structural alteration. However, the effectiveness of albino biocontrol agents depends on rapid colonisation under favourable environmental conditions. Under winter harvesting conditions low temperatures delay fungal activity and may prevent timely establishment of the applied organism. In addition, exposure to precipitation under field conditions may reduce the persistence of applied inoculum prior to germination, thereby further limiting its effectiveness.

Laboratory experiments have also demonstrated that naturally derived antifungal substances can inhibit decay. Hydroxystilbenes such as resveratrol, piceatannol and isorhapontigenin extracted from spruce debarking wastewater reduced the mycelial growth of brown- and white-rot fungi by up to 90% at concentrations of 100 µg mL^{-1} (Hedenstrom *et al*. 2016). Similarly, essential oils from citronella, cedarleaf and geranium inhibited blue-stain fungi by 50–100%, although their persistence and formulation stability remain limiting factors (Dawson-Andoh *et al*. 2000).

3.3.7. In-ground storage

In-ground storage is an oxygen-limiting preservation method in which roundwood is stacked compactly and covered with a soil or substrate layer that restricts aeration and biological activity. A documented Swiss application after storm *Lothar* stored approximately 1 000 m^3 of spruce and fir beneath a separating fleece and about 1 m of clay-rich excavated material; after 2.5 years, sawn timber quality was comparable to wet-stored logs, with only minor end-stain and no structural defects, although residual clay adhering to the logs increased tool wear during sawing. The reported total storage costs amounted to approximately CHF 25 m^{-3} (17.07€ m^{-3}, exchange rate of 1 June 2002) of timber, including stacking, retrieval, site restoration, and in-house labour and material inputs (Tschannen 2002). Recent pilot trials confirmed that such systems can achieve very low internal oxygen levels. Gypsum-covered spruce piles maintained O_2 concentrations of 0–4% and CO_2 above 11%, accompanied by internal temperatures of 25–33 °C (Becker 2022, as cited in Trautwein *et al*. 2025b). However, the hygroscopic behaviour of gypsum led to substantial moisture loss. Fresh logs dried from 101% to 86% and beetle-infested logs from 76% to 64% within 18 months, promoting discolouration, decay, and consequently downgrading of the material to RVR (Deutscher Forstwirtschaftsrat and Deutscher Holzwirtschaftsrat 2024) quality grade D.

Practical experience indicates that preservation success depends critically on compact piling, early installation before warm periods, and the use of moisture-stable cover materials such as clay-rich soils; any subsidence or cracking of the cover must be repaired immediately to prevent air ingress. These findings collectively show that while in-ground storage can preserve high wood quality when moisture remains stable, performance is highly sensitive to substrate selection, site conditions, and the ability to avoid unintended drying. However, evaluations of this method and the effect on spruce wood quality remain scarce and further research is needed.

3.3.8. Live storage

Live storage represents a special form of interim preservation in which storm-felled spruce trees are left in situ with their uprooted but still intact root plates remaining in contact with the soil. This continued soil contact enables residual water uptake, substantially slowing desiccation compared with logs that have been severed from the stump. Under these conditions, winter-storm-felled Norway spruce typically maintains high sapwood moisture throughout the first growing season, with only limited blue-stain development on moist or shaded sites where the evaporation rate is low (Jonsson 2007, Blom and Thörnqvist 2014). In contrast, trees lying fully exposed to sun and wind dry markedly faster, leading to earlier onset of staining fungi (Jonsson 2007). Grading studies demonstrate the time-limited preservation potential: after six months, nearly all spruce boards produced from live-stored stems still met the two highest DIN quality classes, whereas after twelve months this proportion had decreased to 35–65%, reflecting progressive moisture loss and increasing insect activity (Bücking *et al*. 1997). When live storage extends into a second summer, drying accelerates sharply and widespread blue stain and decay become common, making quality preservation no longer feasible (Jonsson 2008). After eighteen months of live storage, quality decline becomes pronounced, with continued desiccation and markedly higher frequencies of insect- and fungus-related defects further reducing the share of boards eligible for higher log grades (Bücking *et al*. 1997).

3.3.9. Standing storage

Standing storage refers to the practice of leaving beetle-killed spruce trees unharvested on the stump for extended periods, during which the wood remains exposed to progressive biological and physical degradation. Standing storage of beetle-killed spruce results in a characteristic progression of wood-quality changes driven by staining fungi and decay. In the early post-mortem period, blue-stain fungi introduced by bark beetles colonise the sapwood but have little effect on density, MOE, or bending strength. The mechanical properties remain close to those of freshly cut material (Künniger *et al*. 2024). Discolouration intensity and colonisation depth increase with time, spreading vertically and radially from gallery-rich zones as demonstrated by imaging and fungal isolations in standing dead spruce (Löwe *et al*. 2022). These colonisation pathways facilitate subsequent invasion by decay fungi, marking the transition from predominantly cosmetic deterioration to substantive structural degradation. At the stand level, this transition is reflected in a time-dependent increase in stem breakage, loss of crown integrity, and the occurrence of fungal fruiting bodies, indicating progressive structural degradation during standing storage (Trautwein *et al*. 2025a). The effectiveness of subsequent dry storage is closely linked to prior standing storage, as pre-dried logs exhibit lower initial moisture contents and therefore reach critical thresholds for biological activity more rapidly (Trautwein *et al*. 2026).

4. Discussion

4.1. Storage method and initial wood condition as determinants of degradation pathways

The reviewed literature demonstrates that the development of spruce roundwood quality during storage is governed by the interaction of the process variables moisture availability, oxygen availability, and temperature, which are structured by the storage method. Moisture and temperature jointly govern degradation under dry storage conditions, whereas oxygen availability restricts degradation processes in wet and airtight foil storage systems. Under cold storage, low temperatures constrain biological degradation.

These process variables define the boundary conditions for the applicability of different storage methods. Uncontrolled dry storage is generally unsuitable for freshly felled timber from healthy trees beyond short interim storage periods, as rapid moisture loss under aerobic conditions promotes checking and facilitates fungal colonisation (Webber and Gibbs 1996). In contrast, oxygen-excluding methods such as the

Baden-Württemberg foil storage method rely on the establishment of anaerobic conditions, which in fresh wood result from respiration of living parenchyma cells that deplete residual oxygen within the sealed system. This mechanism suppresses fungal activity but depends on the physiological integrity of the wood. In heavily beetle-infested or dead timber, the lack of living parenchyma cells limits oxygen consumption, preventing sufficiently low oxygen levels and reducing the effectiveness of foil storage (Brischke *et al*. 2020, 2021, Trautwein *et al*. 2025b). Wet storage is most effective when applied to freshly felled wood, as drying may reduce rewetting efficiency and pre-existing fungal colonisation cannot be reversed (Bjurman and Viitanen 1996, Webber and Gibbs 1996, Lukkari *et al*. 2004).

Besides technical considerations, the application of storage methods is constrained by economic factors. Cost-intensive preservation strategies are only justified for high-quality assortments, whereas lower-quality or pre-damaged timber is typically allocated to less expensive storage methods (Trautwein *et al*. 2025a, Trautwein *et al*. 2026).

Environmental and regulatory constraints, particularly related to water use and pollutant emissions, further constrain the applicability of storage methods and must be considered in their selection and implementation (Jonsson *et al*. 2006, Jonsson 2012b).

4.1.1. Dry storage: minimal infrastructure, limited temporal safety

Dry storage is characterised by low infrastructural requirements and high operational flexibility, but it generally provides the shortest safe storage window when compared with oxygen-limited or water-based storage systems. As emphasised by Trautwein *et al*. (2025b) uncovered dry storage exposes logs directly to ambient climatic conditions and is therefore associated with a rapid increase in biological degradation risk, whereas covered dry storage can moderately delay deterioration by reducing precipitation and radiation while maintaining ventilation. Under favourable conditions, spruce logs stored dry may remain processable for several weeks; however, blue-stain fungi and insect infestation often develop within a short time frame, particularly during warm periods and when bark integrity is compromised.

Technical measures such as debarking or bark gouging can extend the usable dry-storage period by removing insect breeding substrate and reducing the effectiveness of bark beetles as vectors of blue-stain fungi, while simultaneously accelerating surface drying. Nevertheless, these measures increase harvesting and handling costs and may introduce additional risks, including enhanced drying gradients and mechanical surface damage, which limit their suitability for extended dry storage durations.

Dry conservation, as a more controlled variant of dry storage, represents a compromise between cost, environmental impact and effectiveness. Its success depends strongly on favourable weather conditions, skilled pile construction and early implementation. Even under optimal conditions, dry conservation cannot prevent chemical and biological degradation indefinitely, and its applicability is therefore limited to short- to medium-term storage scenarios.

4.1.2. Wet and foil storage: long-term preservation with trade-offs

Wet storage by continuous sprinkling and anaerobic storage using airtight foil enclosures are consistently identified as the most effective methods for preserving spruce roundwood quality over multi-year periods. By maintaining high moisture contents and suppressing oxygen availability, these methods effectively inhibit wood-decay fungi and limit structural degradation.

In foil storage, the chemical component is inherently passive. Preservation arises from self-generated or externally introduced gas compositions within the sealed pile. Low-oxygen atmospheres enriched in carbon dioxide or nitrogen act as physicochemical inhibitors that suppress metabolic activity but do not function as biocides. This distinguishes anaerobic storage fundamentally from active chemical treatments. While highly effective, both wet and foil storage face practical constraints related to installation costs, regulatory requirements and environmental concerns, particularly regarding runoff water quality in wet storage systems.

4.1.3. Cold storage: effective but temporally limited

Cold storage has long been applied operationally in boreal regions as a seasonal preservation technique, yet systematic scientific evaluation remains limited. Available evidence is derived primarily from short-term industrial trials conducted within a single winter season, and focuses mainly on visual and mechanical wood properties (Mäkelä *et al*. 2001, Mäkelä and Achren 2003, Mäkelä 2004). These studies consistently demonstrate that, when insulation is properly maintained and premature thawing is avoided, spruce logs can retain mechanical integrity and aesthetic quality comparable to freshly harvested material throughout the cold-storage period without the use of chemical preservatives.

However, several knowledge gaps remain. Spatial variability within log piles, particularly temperature and moisture gradients between surface and core logs, has rarely been quantified in detail. Moreover, standardised testing protocols for optical, mechanical and chemical wood properties are lacking, which limits quantitative comparability among studies. Economic assessments are confined to site-specific cost estimates, and the operational robustness of cold storage under increasingly variable winter conditions remains uncertain.

Importantly, cold storage is inherently constrained by seasonal temperature regimes. Under temperate and boreal climates, storage effectiveness is limited to the winter period, as accumulated ice and insulation inevitably degrade during spring and summer thawing. Consequently, cold storage cannot be considered a multi-year preservation strategy, but rather a time-limited option to bridge winter harvesting and early-season processing. As climate change is expected to reduce snow reliability and shorten periods of sustained sub-zero temperatures, the future applicability and reliability of cold storage as a preservation method requires follow-up investigation.

4.1.4. Situational storage options: live and standing storage

Live storage represents a special case that is best understood as a situational opportunity rather than an active preservation strategy. When storm-felled spruce trees remain uprooted but maintain physiological contact with the soil, water uptake and limited metabolic activity can temporarily delay desiccation and fungal colonisation (Bücking *et al*. 1997, Blom and Thörnqvist 2014). Under such conditions, wood quality may be preserved for several weeks to months. However, the effectiveness of live storage depends critically on sustained root–soil contact and declines rapidly once the hydraulic connection is disrupted or storage extends beyond a single vegetation period (Jonsson 2007, 2008). Consequently, live storage can only function as a short-term buffer following disturbance events and cannot be relied upon as a controllable management option.

Standing storage likewise reflects a capacity-driven outcome rather than a deliberate strategy. When harvesting and processing capacities are exceeded during large-scale disturbances, damaged spruce stands may remain unharvested for extended periods. Such delays have been repeatedly documented following storm and bark beetle calamities (Schwarzbauer 2006). While standing trees may initially retain acceptable wood quality (Künniger *et al*. 2024), the progression of sap-stain, insect infestation, decay and drying related crack formation in the outer parts of the trunk rapidly limits their suitability for high-value assortments (Löwe *et al*. 2022, Trautwein *et al*. 2025a). Once discolouration becomes extensive or decay processes are established, quality losses accelerate and recovery of value through later harvesting becomes unlikely.

4.2. Biological agents: from superficial moulds to structural decay

The reviewed studies highlight that biological degradation during storage spans a continuum from superficial mould colonisation to advanced structural decay. Superficial mould fungi such as *Trichoderma*, *Penicillium* and *Aspergillus* spp. colonise parenchyma cells near the wood surface and metabolise readily available nutrients including monosaccharides, polysaccharides, proteins and fatty acids (Daniel 2016, Schrader *et al*. 2025). Although cosmetically undesirable, these moulds do not degrade lignin or cellulose and therefore do not impair mechanical strength (Schmidt 2006).

In contrast, wood-decay fungi represent the most economically significant biological threat to timber durability (Schrader *et al*. 2025). Brown-rot fungi, which dominate in many storage contexts, employ a combined chemical and enzymatic degradation mechanism. By releasing low-molecular-weight compounds such as oxalic acid, they generate hydroxyl radicals that depolymerise cellulose and hemicelluloses, while lignin remains largely unmodified. Crucially, decay requires the presence of free (liquid) water, as fungal hyphae cannot access water tightly bound within the cell wall. Consequently, wood moisture contents must exceed fibre saturation, which typically lies between 25% and 35% depending on species (e.g. *P. sitchensis:* 25% (Barkas 1935)), for decay to occur. This mechanistic requirement explains why decay is largely suppressed in well-managed dry storage and cold storage, but prevalent in inadequately drained wet systems.

4.3. Chemical transformations and implications for processing

Beyond biological degradation, storage-induced chemical changes increasingly emerge as a relevant but underexplored dimension of wood quality development. Significant losses of extractives have been reported for spruce wood segments stored for eight months (Čabalová *et al*. 2021). Because extractives contribute to the hydrophobic character of the cell wall, their reduction may affect hygroscopicity, dimensional stability and interactions with adhesives or coatings.

Although not investigated on spruce, recent work on corn stover demonstrates that prolonged unprotected storage can lead to hemicellulose degradation and a collapse of the lignin macromolecular structure (Zeng *et al*. 2025). This structural alteration reduces monomer yields during alkaline oxidation and alters lignin properties, indicating that storage-related quality loss extends beyond mechanical deterioration to fundamental chemical transformations of the cell wall. While direct transfer of these findings to spruce must be done cautiously, they highlight the potential for analogous processes in woody biomass under unfavourable storage conditions.

Recent advances in spectroscopic analysis further underline the relevance of such transformations. Fourier-transform infrared (FTIR) spectroscopy has emerged as a sensitive tool for detecting storage-related chemical changes in lignocellulosic materials, including oxidation of functional groups, alterations in carbohydrate signatures, and lignin structural modifications. Although FTIR-based approaches have so far been applied predominantly to agricultural residues and processed biomass (Prinz *et al*. 2024), their underlying principles are equally applicable to softwoods. For spruce logs, FTIR could provide insights into extractive depletion, hemicellulose degradation, or lignin condensation occurring during interim storage, thereby complementing conventional assessments focused on visible or mechanical deterioration.

Such chemical changes have direct implications for industrial processing. Lignin condensation and hemicellulose loss can reduce pulp yield, impair bleachability and affect downstream processing efficiency. Consequently, assessments of stored roundwood quality should increasingly incorporate chemical indicators alongside visual and mechanical criteria.

4.4. Emerging analytical tools and future research directions

Near-infrared (NIR) spectroscopy offers promising opportunities for non-destructive detection of storage-induced chemical modifications. Although its application to spruce roundwood storage remains limited, the sensitivity of NIR spectra to hydroxyl groups, carboxylic acids and aromatic structures suggests potential for discriminating storage history and degradation state. Future research could exploit spectroscopic fingerprints associated with hemicellulose loss, lignin condensation or extractives oxidation to enable rapid, in-field quality assessment of stored logs.

Chemical and biological treatments represent another promising research frontier. Where wet or foil storage is impractical, environmentally compatible antifungal compounds and biocontrol organisms may provide viable alternatives, given they are applied early and under favourable climatic conditions. In addition, recent research on bio-based wood chip pile covers shows that such systems can reduce rewetting and moderate dry matter losses during outdoor storage while avoiding fossil-based plastics (Prinz *et al*. 2022). Although these studies focus on comminuted stem-wood, the underlying mechanisms are directly relevant to spruce log storage. Adapting bio-based cover concepts to log piles may therefore offer a low-impact option to limit biological activity and chemically driven degradation during interim storage, particularly in sensitive or remote locations. However, their effectiveness for roundwood, including impacts on moisture gradients, fungal colonisation, and chemical stability, remains to be evaluated. Integrating such protective measures into combined, low-impact storage systems tailored to operational constraints should be prioritised in future research.

4.5. Synthesis

Building on the analytical framework, the reviewed evidence was synthesised into a qualitative, multi-criteria comparison of major spruce roundwood storage methods using comparative criteria reflecting economic, environmental, operational, and preservation-related trade-offs (Figure 3). Operational scalability thereby refers to the feasibility of applying a storage method to large timber volumes and real operational conditions, considering infrastructure, labour and logistical requirements. Scores were assigned on an ordinal scale (1 = very low, 5 = very high) and represent literature-based tendencies and

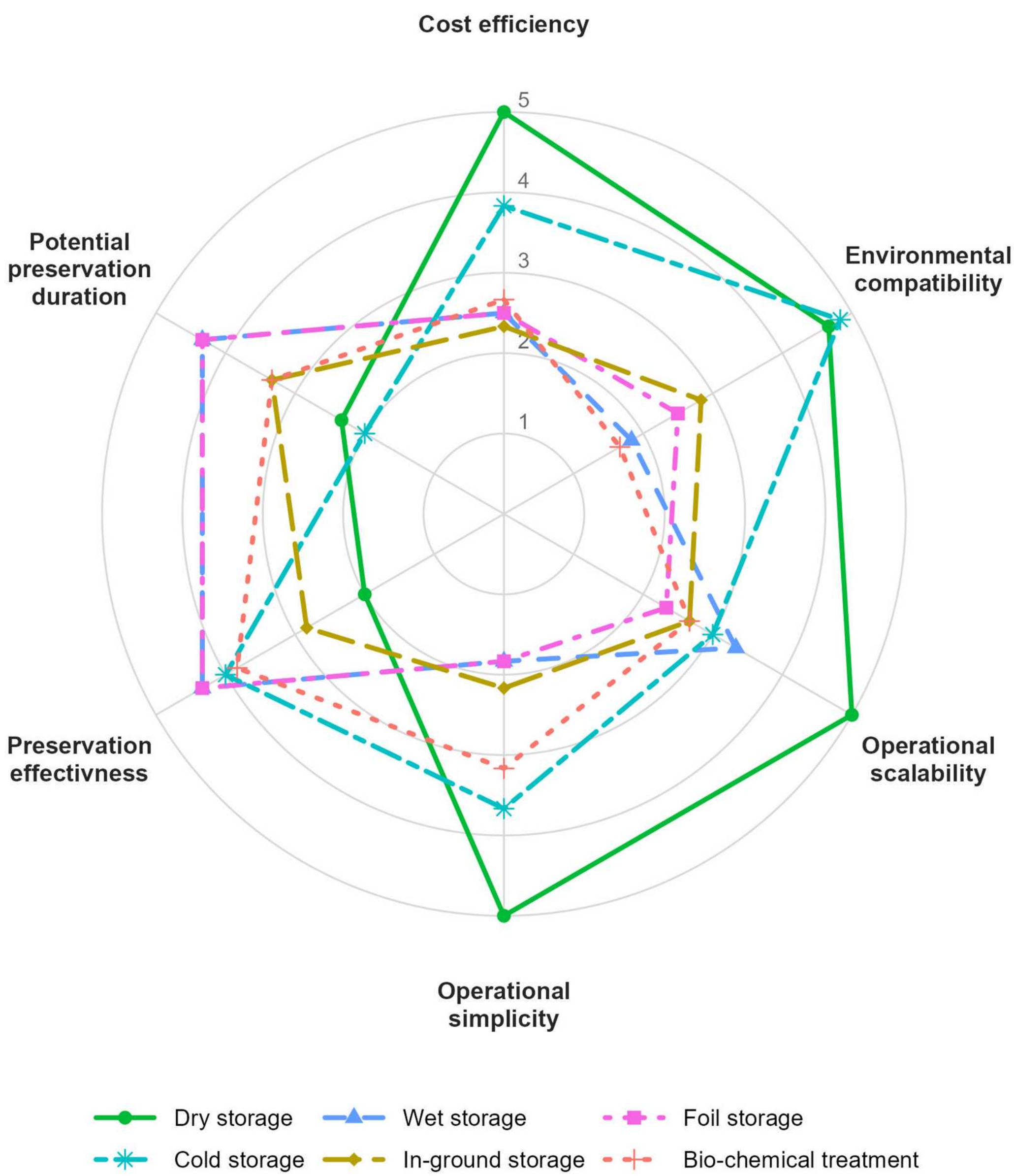

Figure 3. Qualitative radar chart synthesising relative strengths and limitations of major spruce roundwood storage methods across six comparative criteria: cost efficiency, environmental compatibility, operational scalability, operational simplicity, preservation effectiveness, and potential preservation duration. Scores are ordinal (1 = very low, 5 = very high) and represent literature-based tendencies rather than measured performance values. All criteria are oriented such that higher scores indicate more favourable performance. The chart illustrates characteristic, method-level performance profiles, aggregating variability among sub-methods and operational contexts.

the authors' synthesis and expert judgement rather than empirically measured performance values, thereby enabling method-level comparison without implying quantitative equivalence.

The synthesis demonstrates that no single storage method optimally fulfils all criteria. Dry storage offers high cost efficiency and operational scalability but only short-term quality preservation. Wet and foil storage enable extended preservation with high preservation effectiveness, albeit at the expense of increased operational effort and environmental or material constraints. Cold storage provides effective but strictly seasonal preservation, while in-ground storage represents a situational, intermediate option with limited controllability and low simplicity. Chemical and biological treatments show promise for degradation control, yet remain operationally demanding and context-dependent. Overall, storage selection emerges as a context-specific balancing act shaped by temporal constraints, infrastructure availability, and targeted quality objectives.

5. Conclusion

This review synthesised published evidence on the effects of different storage methods on the biological, chemical and physical quality development of spruce (*Picea* spp.) roundwood. The results confirm that storage environment is the primary determinant of degradation pathways, with moisture availability, oxygen availability and temperature acting as fundamental process variables, while the suitability of individual storage methods also depends on the initial condition and quality of the stored timber.

This study integrates biological, chemical and physical quality indicators within a structured framework and relates them to process variables governing wood degradation. By combining quantitative evidence synthesis with qualitative evaluation, it enables a comparative, method-level interpretation of storage performance and its underlying mechanisms.

Wet storage and anaerobic foil storage consistently provide the most reliable preservation of structural wood quality over extended periods, whereas dry storage offers only short-term protection and requires strict control of bark condition and climatic exposure. Cold storage represents an effective and environmentally safe option under boreal conditions, but its long-term reliability and performance under changing winter climates remain open. Situational options such as live and standing storage may temporarily delay degradation but cannot be considered deliberate storage methods.

Across storage methods, biological degradation dominates visible quality losses, while storage-induced chemical changes, such as extractive depletion and potential lignocellulosic alteration, remain underrepresented in the literature despite their relevance for industrial processing. Standardised assessment protocols and integrated analytical approaches are largely lacking.

Future research should therefore focus on integrating different wood quality indicators, advancing non-destructive monitoring techniques and developing low-impact preservation strategies suitable for operational constraints. Such advances are essential to improve decision-making in disturbance-driven timber supply chains and to mitigate value loss during interim storage.

Author contributions

CRediT: **Stephan Böhm:** Conceptualization, Formal analysis, Investigation, Project administration, Visualization, Writing – original draft, Writing – review & editing; **Axel Solt-Rindler:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing; **Oliver Vay:** Writing – original draft, Writing – review & editing; **Robert Prinz:** Funding acquisition, Investigation, Writing – review & editing; **Michael Grabner:** Conceptualization, Funding acquisition, Writing – review & editing; **Christian Kanzian:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research has received funding from the 'OptiForValue' project which is supported by the Circular-based Europe Joint Undertaking and its members under Grant Agreement N101157658 funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CBE JU. Neither the European Union nor the CBE JU can be held responsible for them. The research has also received funding from the project 'InnoLa – Innovative Lagerung von Rundholz in Schadholzkalamitäten' by the Austrian Waldfonds – M4_Errichtung Holzlagerplätze und Schadholztransport (Federal ministry of Agriculture and Forestry, Climate and Environmental protection, Regions and Water management, Republic of Austria).

ORCID

Stephan Böhm http://orcid.org/0000-0001-7803-6618
Axel Solt-Rindler http://orcid.org/0000-0002-6151-8490
Oliver Vay http://orcid.org/0000-0002-6105-7735
Robert Prinz http://orcid.org/0000-0002-1593-6974
Michael Grabner http://orcid.org/0000-0002-5220-721X
Christian Kanzian http://orcid.org/0000-0002-1198-9788

References

Adolf, P., Gerstetter, E., and Liese, W., 1972. Untersuchungen über einige Eigenschaften von Fichtenholz nach dreijähriger Wasserlagerung. *Holzforschung*, 26, 18–25. https://doi.org/10.1515/hfsg.1972.26.1.18.

Anonymous, 1995. High-quality construction timber through dry preservation [Qualitätsbauholz via Trockenkonservierung]. Holz-Zent.bl.

Anonymous, 2002. Structural timber sawmills on a tightrope: 2003 may prove decisive for many operations [Bauholzsäger vor Drahtseilakt: 2003 dürfte für viele Sägewerke zum Jahr der Entscheidung werden]. Holz-Zent.bl.

Anonymous, 2006. Wet storage for securing summer timber supply [Nasslagerung zur Sicherung der Sommerversorgung]. Holz-Zent.bl.

Anonymous, 2019. Demand-based control of sprinkler irrigation in wet storage: Swedish manufacturer Kagon reduces water consumption and adverse effects with an individually controlled system [Beregnung im Nasslager bedarfsgerecht steuern: Schwedischer Hersteller Kagon verringert mit individuell gesteuertem System Wasserverbrauch und negative Effekte]. Holz-Zent.bl.

Anonymous, 2020a. Foil storage proves effective in trials: even after one and a half years, the stored bark beetle-damaged timber retains its quality [Folienlagerung funktioniert im Versuch: Auch nach anderthalb Jahren hält das eingelagerte Borkenkäferholz seine Qualität]. Holz-Zent.bl.

Anonymous, 2020b. FVS moves storm-damaged timber from recent months into wet storage; forestry association jointly shoulders the investments [FVS bringt Sturmholz der letzten Monate in Nasslager: Forstwirtschaftlicher Zusammenschluss stemmt Incestitionen solidarisch]. Holz-Zent.bl.

Anonymous, 2020c. State forest and timber enterprise NRW tests foil storage for bark beetle-damaged timber: promising results after one year of storage [Landesbetrieb Forst und Holz NRW testen Folienlagerung für Käferholz: Nach einem Jahr Lagerung zeigte sich ein vielversprechendes Ergebnis]. Holz-Zent.bl.

Anonymous, 2021. Tests raise hope: foil storage preserved wood quality for two years [Tests wecken Hoffnung: Folienlager hat Holzqualität zwei Jahre lang bewahrt]. Holz-Zent.bl.

Anonymous, 2024. Still B- and C-grade quality after five years [Nach fünf Jahren noch B- und C-Qualität]. Holz-Zent.bl.

Asada, R., *et al*., 2023. Resilient forest-based value chains? Econometric analysis of roundwood prices in five European countries in the era of natural disturbances. *Forest Policy and Economics*, 153, 102975. https://doi.org/10.1016/j.forpol.2023.102975.

Aufsess, H. and Pechmann, H., 1970. Experiences on the effects of long-term water storage on the quality of softwood roundwood [Erfahrungen über die Auswirkungen längerer Wasserlagerung auf die Qualität von Nadelstammholz]. *Forstwiss. Centralbl*, 89, 65–77.

Aufsess, H., Pechmann, H., and Lippemeier, P., 1974. Some experience with sprinkling of softwood timber [Einige Erfahrungen mit der Berieselung von Nadelrundholz]. *Forstwissenschaftliches Centralblatt*, 93, 296–305. https://doi.org/10.1007/BF02736166.

Avramidis, S., Lazarescu, C., and Rahimi, S., 2023. Basics of wood drying. *In*: P Niemz, A Teischinger, D Sandberg, eds. *Springer handbook of wood science and technology*. Cham: Springer International Publishing, 679–706. https://doi.org/10.1007/978-3-030-81315-4_13

Barkas, W.W., 1935. Fibre saturation point of wood. *Nature*, 135, 545. https://doi.org/10.1038/135545b0.

Beal, E., Webber, J.F., and Eaton, R.A., 2010. Comparative susceptibility of pine, spruce and larch to sapstain. *Forest Pathology*, 40, 116–128. https://doi.org/10.1111/j.1439-0329.2009.00616.x.

Biometria, 2019. Swedish regulations for timber measurement.

Bjurman, J. and Viitanen, H., 1996. Effect of wet storage on subsequent colonisation and decay by Coniophora puteana at different moisture contents. *Mater. Org*, 30, 259–277.

Blom, Å. and Thörnqvist, T., 2014. Live storage and drying of storm-felled Norway spruce (Picea abies, L. Karst.) and Scots pine (Pinus sylvestris L.) trees. *Wood Material Science & Engineering*, 9, 209–213. https://doi.org/10.1080/17480272.2014.881914.

Böhm, S., *et al*., 2023. Blue-stain development on Norway spruce logs under alpine conditions. *Silva Fennica*, 57, 23054. https://doi.org/10.14214/sf.23054.

Böhm, S., *et al*., 2025. The effect of processor debarking on wood quality deterioration during the interim storage of Norway spruce logs. *Forest Ecology and Management*, 586, 122672. https://doi.org/10.1016/j.foreco.2025.122672.

Brischke, C., *et al*., 2020. Foil storage of bark beetle-infested timber: evaluation of the expected protective performance [Folienlagerung von Käferholz: Untersuchung der zu erwartenden Schutzwirkung]. Holz-Zent.bl.

Brischke, C., *et al*., 2021. Foil storage for conservation of beetle-infested spruce logs – a feasibility study. *Pro Ligno*, 17, 11–17.

Brischke, C. and Wippermann, K., 2022. Foil storage of storm-felled timber – long-term monitoring of Norway spruce piles in Germany. *Forests*, 13, 1918. https://doi.org/10.3390/f13111918.

Bücking, M., *et al*., 1997. Investigations on the live-storage of windthrown timber of the tree species Norway spruce, Scots pine Douglas-fir and oak [Untersuchungen zur Lebendlagerung von Sturmwurfholz der Baumarten Fichte, Kiefer, Douglasie und Eiche]: Mitteilungen aus der Forstlichen Versuchsanstalt Rheinland-Pfalz; 42. Forstliche Versuchsanst. Rheinland-Pfalz, Trippstadt.

Bues, C.T., 1986. Investigations of some properties of fir and spruce wood after 17 years' water storage [Untersuchung einiger Eigenschaften von Tannen- und Fichtenholz nach 17jähriger Wasserlagerung]. *Holz als Roh- und Werkstoff*, 44, 7–15. https://doi.org/10.1007/BF02616307.

Bues, C.T. and Weber, A., 1998. Log storage using a new technique [Eine neue Methode der Rundholzlagerung]. *Forstwissenschaftliches Centralblatt*, 117, 231–236. https://doi.org/10.1007/bf02832976.

Čabalová, I., *et al*., 2021. Chemical and morphological composition of Norway spruce Wood (Picea abies, L.) in the dependence of its storage. *Polymers*, 13, 1619. https://doi.org/10.3390/polym13101619.

Čabalová, I., *et al*., 2023. Evaluation of chemical and morphological properties of spruce wood stored in the natural environment. *Polymers*, 15, 4734.

Čabalová, I., 2025. *Spruce wood and the change in its chemical properties during storage*. Lüdenscheid: RAM-Verlag.

Christiansen, E. and Bakke, A., 1988. The spruce bark beetle of eurasia. *In*: A.A. Berryman, ed. *Dynamics of forest insect populations*. Boston, MA: Springer US, 479–503. https://doi.org/10.1007/978-1-4899-0789-9_23

CTBA, 2004. Technical guide on harvesting and conservation of storm damaged timber.

Dahm, H.P., 1966. A comparison of log storage and chip storage of spruce. Norsk. Skokind 20.

Daniel, G., 2016. Chapter 8 – fungal degradation of wood cell walls. *In*: Y.S. Kim, R. Funada, A.P. Singh, eds. *Secondary xylem biology*. Boston: Academic Press, 131–167. https://doi.org/10.1016/B978-0-12-802185-9.00008-5

Dawson-Andoh, B.E., Lovell, R., and Kamdem, D.P., 2000. Inhibitory and compatibility effects of essential oils on sapstain and biological control fungi. *Journal of Essential Oil Research*, 12, 509–515. https://doi.org/10.1080/10412905.2000.9699577.

Deutscher Forstwirtschaftsrat, e., and Deutscher Holzwirtschaftsrat, e., 2024. Framework agreement for the raw timber trade in Germany (RVR) [Rahmenvereinbarung für den Rohholzhandel in Deutschland (RVR)]: 6., aktualisierte Auflage, 16. Dezember 2024.

Dimou, V., 2012. Harvest-time related blue-stain spread in logs in the forest of Elatia, Greece. *Wood Research*, 57, 241–250.

DIN 52185:1976-09. Testing of wood; compression test parallel to grain [Prüfung von Holz; Bestimmung der Druckfestigkeit parallel zur Faser], Berlin. https://doi.org/10.31030/1260162.

DIN 52186:1978-06. Testing of wood; bending test [Prüfung von Holz; Biegeversuch], Berlin. https://doi.org/10.31030/1260171.

DIN 52189-1:1981-12. Testing of wood; impact bending test; determination of impact bending strength [Prüfung von Holz; Schlagbiegeversuch; Bestimmung der Bruchschlagarbeit], Berlin. https://doi.org/10.31030/1260206.

DIN 68364:2003-05. Properties of wood species – density, modulus of elasticity and strength [Kennwerte von Holzarten - Rohdichte, Elastizitätsmodul und Festigkeiten], Berlin. https://doi.org/10.31030/9479339.

DIN EN 1927-1 :2008-06. Qualitative classification of softwood round timber – part 1: spruces and firs; German version EN 1927-1:2008, Berlin. https://doi.org/10.31030/1391641.

Efransjah, F., Kilbertus, G., and Bucur, V., 1989. Impact of water storage on mechanical properties of spruce as detected by ultrasonics. *Wood Science and Technology*, 23, 35–42. https://doi.org/10.1007/BF00350605.

EN 252:2015-01. Field test method for determining the relative protective effectiveness of a wood preservative in ground contact; CEN European Committee for Standardization.

Fachverband der Holzindustrie Österreichs. Austrian wood trade conventions [Österreichische Holzhandelsusancen, ÖHU].

FAO, 2021. Joint forest sector questionnaire definitions. https://openknowledge.fao.org/handle/20.500.14283/cb4108en [Accessed 21 Apr 2026].

Fengel, D. and Wegener, G., 1988. Chemical analyses of spruce wood after 17 years water storage [Chemische Analysen von Fichtenholz nach 17jähriger Wasserlagerung]. *Holz als Roh und Werkstoff*, 46, 7–8. https://doi.org/10.1007/BF02630546.

Francke-Grosmann, H., 1939. On the association between wood wasps (Siricinae) and fungi [Über das Zusammenleben von Holzwespen (Siricinae) mit Pilzen]. *Zeitschrift für Angewandte Entomologie*, 25, 647–680. https://doi.org/10.1111/j.1439-0418.1939.tb01165.x.

Fuchs, J.M., *et al*., 2022. Quantifying the consequences of disturbances on wood revenues with impulse response functions. *Forest Policy and Economics*, 140, 102738. https://doi.org/10.1016/j.forpol.2022.102738.

Geibler, A. and Scholz, H., 2008. Foil storage has proven successful in Saxony. As part of a joint project between Klausner Holz Sachsen and Sachsenforst, 25,000 m^3 of storm-damaged timber were stored. [Folienlagerung hat sich in Sachsen bewährt: Im Rahmen eines Gemeinschaftsprojetks von Klausner Holz Sachsen und Sachsenforst wurden 25000 Fm Sturmholz eingelagert]. Holz-Zent.bl.

Golser, M., Pichler, W., and Hader, F., 2005. Fuelwood drying: final report [Energieholztrocknung: Endbericht]. Koorperationsabkommen Forst-Platte-Papier.

Göttsche-Kühn, H., and Frühwald, A., 1986. Wood properties of spruce from sites subject to environmental pollution investigation after storage in a forest log yard: [Holzeigenschaften von Fichten aus Waldschadensgebieten]. *Holz als Roh und Werkstoff*, 44, 313–318. https://doi.org/10.1007/BF02628007.

Groß, M. and Lübbers, P., 1992. Development of discoloration and moisture content in fir and spruce wood after one year of sprinkler storage [Entwicklung der Verfärbung und der Holzfeuchte von Tannen- und Fichtenholz nach einjähriger Beregnung]. *Holz als Roh und Werkstoff*, 50, 456. https://doi.org/10.1007/BF02662788.

Groß, M., Mahler, G., and Klebes, J., 1993. Erfahrungen mit der Rundholzkonservierung durch Schnittflächenversiegelung und Folienabdeckung. Holz-Zentralblatt.

Groß, M. and Metzler, B., 1995. Appearence and spreading of Armillaria mellea s.l. in water sprinkled piles of timber [Auftreten und Ausbreitung von Hallimasch in Beregnungspoltern]. *European Journal of Wood and Wood Products*, 53, 147–153. https://doi.org/10.1007/BF02716415.

Groß, M., Metzler, B., and Schumacher, P., 1996. Armillaria infestation in sprinkler-stored stormwood [Hallimaschbefall an beregnetem Sturmholz]. *AFZ-Der Wald*, 51, 329–332.

Hartig, T., 1844. Ambrosia des Bostrichus dispar. Allg Forst Jagdztg 13.

Hauschild, R., 2021. Mixed results from foil storage: experiences with preserving spruce assortments using the "Woodpacker" method at the Niedersächsische Landesforsten [Folienlagerung mit "Licht und Schatten": Erfahrungen mit der Konservierung von Fichten-Abschnittennach dem "Woodpacker-Verfahren" bei den NLF]. Holz-Zentralblatt.

Hedenstrom, E., *et al*., 2016. Resveratrol, piceatannol, and isorhapontigenin from Norway spruce (Picea abies) debarking wastewater as inhibitors on the growth of nine species of wood-decaying fungi. *Wood Science and Technology*, 50, 617–629. https://doi.org/10.1007/s00226-016-0814-4.

Hildén, L., *et al*., 2006. Distribution and characterisation of discolouring substances in Norway spruce (Picea abies L. Karst.) pulp wood stored under water sprinkling. *Holzforschung*, 60, 93–98. https://doi.org/10.1515/HF.2006.016.

Hnatek, J., *et al*., 2021. Fumigation of insect-infested wooden logs by EDN using two scenarios of plastic tent-tarpaulin sealing: wooden logs stacks placed on bottom plastic sheets or directly on underlying soil. *Sustainability-Basel*, 13, 13377. https://doi.org/10.3390/su132313377.

Hrčka, R., Kučerová, V., and Hönig, V., 2022. Dry-matter loss and changes in the chemical composition of spruce wood after long-term storing in the form of roundwood. *Polymers*, 16, 3400. https://doi.org/10.3390/polym14163400.

Jonsson, M., 2004. Wet storage of roundwood – effects on wood properties and treatment of runoff water, SLU, SE-750 07 Uppsala, Sweden.

Jonsson, M., 2006. Storage of debarked Picea abies saw logs in Sweden. *For. Stud*, 45, 142–149.

Jonsson, M., *et al*., 2006. Treatment of log yard run-off by irrigation of grass and willows. *Environ. Pollut*, 139, 157–166. https://doi.org/10.1016/j.envpol.2005.04.026.

Jonsson, M., 2007. Live storage of Picea abies in Sweden after storm felling. *Scandinavian Journal of Forest Research*, 22, 344–350. https://doi.org/10.1080/02827580701478404.

Jonsson, M., 2008. Live-storage of Picea abies for two summers after storm felling in Sweden. *Silva Fennica*, 42, 246. https://doi.org/10.14214/sf.246.

Jonsson, M., 2012a. Dry and wet storage of Picea abies and Pinus contorta roundwood with and without bark. *Wood Material Science and Engineering*, 7, 41–48. https://doi.org/10.1080/17480272.2012.654819.

Jonsson, M., 2012b. The importance of debarking in mitigating the leaching of pollutants from common Swedish tree species submerged in water. *Journal of Wood Science*, 58, 251–258. https://doi.org/10.1007/s10086-011-1241-7.

Kärvemo, S., *et al*., 2023. Different triggers, different stories: bark-beetle infestation patterns after storm and drought-induced outbreaks. *For. Ecol. Manage*, 545, 121255. https://doi.org/10.1016/j.foreco.2023.121255.

Kirisits, T., 2004. Fungal associates of European bark beetles With special emphasis on the ophiostomatoid fungi. *In*: F. Lieutier, K.R. Day, A. Battisti, J.-C. Grégoire, H.F. Evans, eds. *Bark and wood boring insects in living trees in Europe, a synthesis*. Dordrecht: Springer Netherlands, 181–236. https://doi.org/10.1007/978-1-4020-2241-8_10

Klaiber, V. and Seeling, U., 2002. Importance of type and duration of the roundwood storage of Norway spruce (Picea abies (L.) Karst.) for the drying behaviour of the sawn timber [Bedeutung von art und dauer der rundholzlagerung von fichten (Picea abies (L.) Karst.) für das trocknungsverhalten des schnittholzes]. *Holz als Roh und Werkstoff*, 60, 421–432. https://doi.org/10.1007/s00107-002-0330-0.

Klaiber, V.V., *et al*., 2002. Reduction of the moisture content in logs of Norway spruce (Picea abies (L.). Karst.) as a function of type and duration of the storage - estimation with a cohort sequential analysis [Veränderung der Holzfeuchte im Rundholz von Fichten (Picea abies (L.) Karst.) in Abhängigkeit von Art und Dauer der Lagerung - Abschätzung mittels einer Kohorten-Sequenzanalyse]. *Allg. Forst Jagdztg*, 173, 162–172.

Kleist, G., 2001. Red streak in spruce wood-a fungal damage and its causes [Rotstreifigkeit im Fichtenholz - ein Pilzschaden und seine Ursachen]. *Z. Mykol*, 67, 213–224.

Künniger, T., *et al*., 2024. Mechanical properties of Norway spruce (Picea abies) infested by the bark beetle (Ips typographus). *Wood Material Science & Engineering*, 19, 85–91. https://doi.org/10.1080/17480272.2023.2226644.

Lind, T., *et al*., 2004a. Dry-storage and water sprinkling of spruce pulpwood. Part 1. Effects on wood properties. *Paperi Ja Puu*, 86, 450+.

Lind, T., *et al*., 2004b. Dry-storage and water sprinkling of spruce pulpwood. Part 2.: Effects on groundwood pulp properties. *Paperi Ja Puu*, 86, 561–564.

Liukkoxs, K. and Elowsson, T., 1999. The effect of bark condition, delivery time and climate-adapted wet storage on the moisture content of Picea abies (L.) Karst. pulpwood. *Scand. J. For. Res*, 14, 156–163.

Loras, V., 1974. Bleachability of mechanical pulp. *Tappi Journal*, 57, 98–102.

Löwe, R., *et al*., 2022. How bark beetle attack changes the tensile and compressive strength of spruce wood (Picea abies (L.) H. Karst.). *Forests*, 13, 87. https://doi.org/10.3390/f13010087.

Lukkari, J., *et al*., 2004. Preservation of wood quality [Puun laadun säilyttäminen – opas].

Lutze, M., 2014. From one calamity to the next: long-term roundwood storage concepts are crucial for effective disaster preparedness [Nach der Kalamität ist vor der Kalamität: Konzepte zur langfristigen Rundholzlagerung sind wichtige Bausteine einer erfolgreichen Katastrophenvorsorge]. LWF aktuell 99.

Maier, T., *et al*., 2002. Foil preservation of roundwood now ready for practical application: assessment of a new method after "Lothar" [Folienkonservierung von Rundholz jetzt praxisreif: Bilanz eines neuen Verfahrens nach "Lothar"]. Holz-Zentralblatt.

Maier, T., 2005. Preservation of timber in low oxygen atmosphere [Konservierung von Rundholz unter Sauerstoffabschluss - Folienkonservierung], Fakultät für Forst- und Umweltwissenschaften der Albert-Ludwigs-Universität Freiburg.

Mäkelä, M., 2002. Development of cold storage technique [Kylmävarastointitekniikan kehittäminen]. Metsätehon raportti 140.

Mäkelä, M., 2004. Preserving the quality of spruce and birch plywood logs [Kuusikuitupuun ja koivuvaneri-tukkien laadun säilyttäminen]. Metsätehon raportti 165.

Mäkelä, M. and Achren, S., 2003. Maintaining the quality of pulpwood [Sellupuun laadun säilyttäminen]. Metsätehon raportti 145.

Mäkelä, M., Korhonen, K., and Lipponen, K., 2000. Effect of storage on pulpwood. English version of Metsätehon raportti 91B.

Mäkelä, M. and Pennanen, O., 1980. Damage to the manufacture and storage of saw logs- the importance of production and storage damage in saw logs across different delimbing methods [Sahatukkien valmistus- ja varastointivaurioiden merkitys eri karsintamenetelmissä]. Metsätehon katsaus.

Mäkelä, M., Varhimo, A., and Pennanen, O., 2001. Winter-felled spruce pulpwood cold storage [Talvikaatoisen kuusikuitupuun kylmävarastointi]. Metsätehon raportti 107.

Malan, F.S., 2004. Some notes on the effect of wet-storage on timber. *Southern African Forestry Journal*, 2004, 77–82.

Metzler, B., 1994. Oxygen supply of Armillaria in wet spruce wood [Die Luftversorgung des Hallimasch in nassem Fichtenholz]. *Nachrichtenbl. Dtsch. Pflanzenschutzdienst*, 46, 292–294.

Metzler, B. and Hecht, U., 2004. Three-dimensional structure of tubular air channels formed by Armillaria spp. in water-saturated logs of silver fir and Norway spruce. *Canadian Journal of Botany*, 82, 1338–1345. https://doi.org/10.1139/B04-092.

Metzler, V., Groß, M., and Mahler, G., 1993. Fungal growth in spruce timber stored under low-oxygen atmosphere [Pilzentwicklung in Fichtenholz unter Schutzgasatmosphäre]. *European Journal of Forest Pathology*, 23, 281–289. https://doi.org/10.1111/j.1439-0329.1993.tb00964.x.

Michalec, K., *et al*., 2024. Dynamics of wood decay in the cross-section of logs as a result of long-term storage in a landing yard. *Drewno*, 67, 214. https://doi.org/10.53502/wood-192478.

Morin, C., *et al*., 2006. Bioprotection of spruce logs against sapstain using an albino strain of Ceratocystis resinifera. *Phytopathol*, 96, 526–533. https://doi.org/10.1094/PHYTO-96-0526.

Mühlhausen, C., 2008a. Ein halber Jahreseinschnitt in Folie verpackt: Erste Untersuchungsergebnisse stimmen positiv. Holz-Zentralblatt.

Mühlhausen, C., 2008b. Proper log-pile formation is crucial: lessons from foil-pile storage of storm timber in Lower Saxony [Gute Polterausformung hat eine Schlüsselrolle: Erfahrungen aus Niedersachsen mit der Sturmholzlagerung im Folienpolter]. *Holz-Zent.bl*.

Münch, E., 1907. Blue stain of coniferous wood III-IV [Die Blaufäule des Nadelholzes I-II]. *Naturwissenschaftliche Zeitschrift für Land- und Forstwirtschaft*, 5, 531–573.

Münch, E., 1908. Blue stain of coniferous wood III-IV [Die Blaufäule des Nadelholzes III-IV]. *Naturwissenschaftliche Zeitschrift für Land- und Forstwirtschaft*, 6, 297–323.

Murphy, G., Kent, T., and Kofman, P.D., 2012. Modeling air drying of sitka spruce (picea sitchensis) biomass in off-forest storage yards in Ireland. *Forest Products Journal*, 62, 443–449. https://doi.org/10.13073/FPJ-D-12-00096.1.

Nicholls, D. and Brackley, A., 2009. House log drying rates in southeast Alaska for covered and uncovered softwood logs. *USDA Forest Service – General Technical Report PNW-GTR*, 1–23.

Oberkobler, 2002. Crucial role of sprinkler water quality in wet storage [Entscheidende Rolle der Beregnungs-Wasserqualität bei der Nasslagerung]. Holz-Zentralblatt.

OpenAI, 2023. Chat GPT (April 8 2025 version) [Large language model]: https://chat.openai.com.

Patacca, M., *et al*., 2023. Significant increase in natural disturbance impacts on European forests since 1950. *Global Change Biology*, 29, 1359–1376. https://doi.org/10.1111/gcb.16531.

Pechmann, H.v., *et al*., 1967. Investigations into red streaking in spruce wood [Untersuchungen über die Rotstreifigkeit des Fichtenholzes]. Forstwiss. Centralbl.

Peek, R.-D. and Liese, W., 1977. The effect of wet storage of wind-thrown trees on water quality [Die Auswirkung der Naßlagerung von Sturmholz auf die Qualität des Ablaufwassers]. *Forstwissenschaftliches Centralblatt*, 96, 348–357. https://doi.org/10.1007/BF02736530.

Persson, E. and Elowson, T., 2001. Moisture content and discoloration of wood during dry and wet storage of Norway spruce (Picea abies (L.) Karst.) pulpwood. *Paperi Ja Puu*, 83, 132–137.

Persson, E., Filipsson, J., and Elowson, T., 2002. Roadside storage of Norway spruce (Picea abies (L.) Karst.) pulpwood - effect on moisture content of climate conditions, felling season and exposure. *Paperi Ja Puu*, 84, 174–178.

Persson, E. and Lindeberg, J., 2001. Changes in metal concentrations during dry- and wet-storage of Norway spruce pulpwood. *Nordic Pulp & Paper Research Journal*, 16, 327–332. https://doi.org/10.3183/npprj-2001-16-04-p327-332.

Prinz, R., *et al*., 2022. Performance of an innovative bio-based wood chip storage pile cover – can it replace plastic tarps? *Energies*, 15, 1680. https://doi.org/10.3390/en15051680.

Prinz, R., *et al*., 2024. Dynamics of decomposition gases and release of volatile organic substances in long-term storage stockpiles of pine bark: focus on mono- and sesquiterpenes. *Industrial Crops and Products*, 222, 119457. https://doi.org/10.1016/j.indcrop.2024.119457.

Rademacher, P. and Hapla, F., 2012. Investigations of wood conservation in spruce logs after storage under plastic foil part II: physical and elasto-mechanical properties of the produced sawn-timber [Untersuchungen zur Holzkonservierung durch Lagerung von Fichtenstämmen unter Folie Teil II: Untersuchungen der physikalischen und mechanischen Eigenschaften des erzeugten Schnittholzes]. *Forstarchiv*, 83, 144–154.

Rademacher, P., Hapla, F., and Leder, B., 2011. Investigations of wood conservation in spruce logs after storage under plastic foil part I: time series of climatic and environmental parameters of the stored wood [Untersuchungen zur Holzkonservierung durch Lagerung von Fichtenstämmen unter Folie Teil I: Zeitreihenmessungen von Klima- und Umweltparametern des gelagerten Holzes]. *Forstarchiv*, 82, 3–9. https://doi.org/10.2376/0300-4112-81-3.

Riguelle, S., *et al*., 2017. Influence of a long-term storage in anaerobic conditions on Norway spruce (Picea abies, L. Karst.) physical and mechanical wood properties. *Wood Material Science and Engineering*, 12, 288–294. https://doi.org/10.1080/17480272.2016.1178668.

Roos, A., 2023. Forest damage and forest supply chains: a literature review and reflections. *International Journal of Forest Engineering*, 34, 330–339. https://doi.org/10.1080/14942119.2023.2240607.

Röser, D., *et al*., 2011. Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. *Biomass and Bioenergy*, 35, 4238–4247. https://doi.org/10.1016/j.biombioe.2011.07.011.

Savory, J.G., 1954. Breakdown of timber by ascomycetes and fungi imperfecti. *Annals of Applied Biology*, 41, 336–347. https://doi.org/10.1111/j.1744-7348.1954.tb01126.x.

Schmidt, O., 2006. Wood and tree fungi: biology, damage, protection, and use. https://doi.org/10.1007/3-540-32139-X.

Schrader, L., *et al*., 2025. Microbial decay of wooden structures: actors, activities and means of protection. *Microbiology and Biotechnology*, 109, 59. https://doi.org/10.1007/s00253-025-13443-z.

Schüler, G. and Wurster, M., 2001. Roundwood preservation under oxygen exclusion [Rundholzkonservierung unter Sauerstoffabschluss]. *AFZ. Der Wald*, 6, 266–267.

Schumacher, P. and Grosser, D., 1995. Armillaria-attack on logs water-sprinkled for several years [Befall länger beregneten Fichtenstammholzes durch Hallimasch (Armillaria spp.) und sonstige Holzpilze]. *Holz als Roh und Werkstoff*, 53, 137–145. https://doi.org/10.1007/BF02716414.

Schwarzbauer, P., 2006. Impacts of damage caused timber harvests on roundwood prices. A quantitative-statistical analysis with the example of Austria [Einflüsse von Schadholzmengen auf Rohholzpreise. Eine quantitativ-statistische Analyse am Beispiel Österreichs]. *Allg. Forst Jagdztg*, 178, 1–8.

Senf, C. and Seidl, R., 2021. Mapping the forest disturbance regimes of Europe. *Nature Sustainability*, 4, 63–70. https://doi.org/10.1038/s41893-020-00609-y.

Sirvio, J., *et al*., 2012. Peroxide bleaching of thermo-mechanical pulp from stored spruce wood. *J-FOR*, 2, 26–31.

Steffen, A., *et al*., 1995a. Dry preservation of coniferous roundwood as an alternative to sprinkling and for the production of dry construction timber (Part 1) [Trockenkonservierung von Nadelrundholz als Alternative zur Berieselung und zur Erzeugung von trockenem Bauholz (Teil 1)].

Steffen, A., *et al*., 1995b. Dry preservation of coniferous roundwood as an alternative to sprinkling and for the production of dry construction timber (Part 2) [Trockenkonservierung von Nadelrundholz als Alternative zur Berieselung und zur Erzeugung von trockenem Bauholz (Teil 2)].

Stuhlmann, C., *et al*., 2012. A new wet storage system for calamity response: a mobile, modularly expandable concept for conserving roundwood assortments within a closed-loop system [Neues Nasslager zur Kalamitätsbewältigung: Mobiles, modular erweiterbares Konzept zur Konservierung von Rundholzabschnitten in einem geschlossenen Kreislaufsystem]. Holz-Zentralblatt.

Thorn, S., *et al*., 2016. Bark-scratching of storm-felled trees preserves biodiversity at lower economic costs compared to debarking. *Forest Ecology and Management*, 364, 10–16. https://doi.org/10.1016/j.foreco.2015.12.044.

Trautwein, J.-F., *et al*., 2025a. Outer appearance of bark-beetle-infested stands of Norway spruce after different standing storage durations: a case study in the Harz Mountains, Germany. *Journal of Forestry Research*, 36, 94. https://doi.org/10.1007/s11676-025-01889-w.

Trautwein, J.-F., *et al*., 2025b. Protection of stored roundwood: methods, efficacy of protective measures, and quality losses. *Discover Forests*, 1, 19. https://doi.org/10.1007/s44415-025-00021-4.

Trautwein, J.-F., *et al*., 2026. Dry storage of Norway spruce log sections – a field experiment to assess wood quality changes. *Wood Material Science & Engineering*, 1–10. https://doi.org/10.1080/17480272.2026.2635658.

Tschannen, W., 2002. Storing storm-damaged timber: in-ground storage is a viable option [Lagerung von Sturmholz: es geht auch im Erdlager]. *Wald Holz*, 83, 48–50.

Webber, J.F. and Gibbs, J.N., 1996. Water storage of timber: experience in Britain. *Forestry Commission Bulletin*, 117. London: HMSO, xvi + 48pp.

Wilhelmsson, L., *et al*., 2010. *D3.5 Methods and models for relating wood properties and storage conditions to process effciency and product quality*. Uppsala, Sweden: Skogforsk Arbetsrapport.

Winter, H., 2009. Effects of different storage conditions on the quality of spruce pulpwood [Auswirkungen verschiedener Lagerungsbedingungen auf die Qualität von Fichtenschleifholz], Universität Hamburg, Fakultüt für Mathematik, Informatik und Naturwissenschaften, Department für Biologie, Zentrum Holzwirtschaft.

Yang, D.-Q., *et al*., 1999. Development of fungal stain in logs of three Canadian softwoods. *For. Prod. J*, 49, 39–42.

Yang, D.Q. and Rossignol, L., 1999. Evaluation of Gliocladium roseum against wood-degrading fungi in vitro and on major Canadian wood species. *Biocontrol Science and Technology*, 9, 409–420. https://doi.org/10.1080/09583159929677.

Zarges, S., *et al*., 2023. Low accuracy bark gouging controls Ips typographus outbreaks while conserving non-target beetle diversity. *Forest Ecology and Management*, 548, 121399. https://doi.org/10.1016/j.foreco.2023.121399.

Zarges, S., *et al*., 2024. Debarking harvesters simultaneously combat the European spruce bark beetle (Ips typographus) and conserve non-target beetle diversity. *Ecological Solutions and Evidence*, 5, e12353. https://doi.org/10.1002/2688-8319.12353.

Zeng, Y., *et al*., 2025. Storage-Induced collapse of lignin macromolecular structure and its impacts on the biorefinery. *ACS Sustainable Chemistry & Engineering*, 13, 12178–12187. https://doi.org/10.1021/acssuschemeng.5c04284”.