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VOC emissions from commercial wood panels using PTR-MS for indoor air quality evaluation

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Introduction: Wood panels, commonly used in cold climates like the Nordic countries for their aesthetic surface and availability, emit volatile organic compounds (VOCs) that can impact indoor air quality and may contribute to health risks, especially with repeated or prolonged exposure. While research has primarily focused on untreated fresh wood, little attention has been given to the VOC emissions from commercial wood panels. This study aims to investigate the VOC emission pattern, intensity, and profile of nine commercially untreated and treated wood panels commonly used in indoor environments, focusing on how wood type and surface treatments influence emission characteristics.

Methods: The study utilizes Proton Transfer Reaction Time-of-Flight Mass Spectrometry combined with passive sampling, offering a more comprehensive analysis of volatile organic compounds, including both volatile and very volatile compounds, which traditional gas chromatography cannot capture. Advanced statistical methods, such as Bayesian posterior, principal component analysis, and hierarchical clustering analysis, were employed to identify key emission contributors and classify emission patterns.

Results: The findings reveal that emission intensity and profiles are influenced by wood type and surface treatments. Pine and oak emitted higher proportions of VOCs, while spruce primarily emitted VVOCs. Glazing, staining, and painting significantly affect emission intensity, with glazing reducing pine total emissions by 81% and increasing them in spruce by 65%. Staining pine reduced VOC emissions by 74% but increased VVOC emissions by 63%, shifting the emission profile. Despite high emission intensity from untreated pine, painting reduced TVOC emissions by 93%, aligning its profile with lower-emission woods like aspen and spruce, making it more suitable for indoor use.

Discussion: The right treatment can transform high-emission woods into materials resembling low-emission species, offering a practical means to mitigate indoor VOC loads.

KEYWORDS

VOC emissions, wood panels, indoor air quality, surface treatments, proton transfer reaction, principal component analysis

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1 Introduction

Air pollution is one of the main problems threatening environmental health (Sheoran et al., 2022; Sadrizadeh et al., 2022). In indoor environments, the most abundant pollutants are volatile organic compounds (VOCs), which are emitted by various products (Duan et al., 2016). VOCs are a diverse group of carbon-based chemicals that readily evaporate into the air at room temperature. These compounds originate from various sources, including building materials, furniture, paints, and adhesives, significantly contributing to indoor air pollution (Salthammer, 2016; Duan et al., 2016). Given that individuals spend approximately 90% of their time indoors, understanding VOC emissions from common materials is crucial for assessing their impact on indoor air quality (IAQ) and human health (Wolkoff, 2018; González-Lezcano, 2023).

Among these materials, wood-based panels are widely used in interior applications due to their aesthetic appeal, durability, sustainability, and availability, particularly in Nordic countries, where they are readily accessible and cost-effective. However, wood products can emit substantial amounts of VOCs, contributing to a range of effects, from unpleasant odors to various health concerns for occupants (Alapieti et al., 2020; Fürhapper et al., 2020). Several studies have indicated that high concentrations of VOCs, particularly terpenes and aldehydes, commonly emitted by wood products, can irritate the eyes and mucous membranes (Kasanen et al., 1999; Risholm-Sundman et al., 1998). On the other hand, wood VOCs may have beneficial effects on human health, such as relaxation (Matsubara and Kawai, 2018), antioxidant and cognitive benefits (Antonelli et al., 2020).

These contrasting effects highlight the complexity of the research field, where both risks and potential advantages must be considered. Understanding the detailed emission profiles of wood VOCs and VVOCs is therefore essential, not only to mitigate adverse impacts but also to explore and harness their possible health-promoting properties. Additionally, the wood industry employs various treatments to enhance the aesthetic appeal or durability of products, leading to variable VOC removal rates (Qin et al., 2020; Jung and Qassimi, 2022) and sometimes producing secondary emissions, depending on the treatment method (Harb et al., 2018), which can have various negative or positive effects on indoor air quality (Pohleven et al., 2019; Perera et al., 2025). For example, Hyttinen et al. (2010) showed that heat-treated wood decreases VOC emissions significantly and changes its composition, with terpenes decreasing from softwood and aldehydes from European aspen. Such insights are particularly relevant for promoting sustainable use of wood in indoor environments, where material selection can balance environmental, health, and wellbeing considerations. While much research has quantified VOC emissions from wood-based materials, most studies have focused on untreated fresh wood (Taiti et al., 2017; Kovačević et al., 2023; Jensen et al., 2001) and air or thermally treated methods (Harb et al., 2018; Pohleven et al., 2019). Limited research has systematically compared and characterized the emission profiles and intensity of commercially engineered wood products intended for interior use (Perera et al., 2025). It remains unclear how different treatments affect air quality, as they may act as barriers that reduce emissions or introduce additional compounds that alter the emission profile (Englund, 1999; Bulian and Fragassa, 2016). Understanding these interactions is essential for selecting materials that minimize indoor air pollution while maintaining desired aesthetic and functional properties.

To accurately quantify VOC emissions, a variety of analytical techniques are used, typically involving passive (static) and active (dynamic) sampling approaches (Ulker et al., 2021). While passive sampling is useful for assessing the static emission potential and total VOC release capacity of materials, active sampling methods are more suitable for investigating long-term VOC emissions under dynamic indoor conditions. Analytical methods supporting these approaches include advanced chamber testing with controlled ventilation, following standardized protocols such as ISO 16000-10 (2006) and ISO 16000-9 (2024), real-time monitoring using Proton Transfer Reaction Mass Spectrometry (PTR-MS) or Photoionization Detectors (PIDs); and compound-specific identification using thermal desorption tubes (e.g., Tenax TA) analyzed by thermal desorption gas chromatography/mass spectrometry (TD-GC/MS) (Schieweck et al., 2007). Additionally, systems such as CLIMPAQ chambers and UV irradiation setups are used to simulate long-term material degradation (Gunnarsen et al., 1994; Liu et al., 2021).

This study characterizes and compares VOC emissions from nine different untreated and treated wood interior panels commonly available in the Norwegian market, using a passive test chamber method combined with Proton Transfer Reaction–Time of Flight–Mass Spectrometry (PTR-TOF-MS). Gas chromatography (GC) combined with a flame ionization detector (FID) is a commonly used and powerful tool for measuring VOC emissions (Jorgensen et al., 1990). However, it is often time-consuming due to the need for extensive sample preparation. Unlike GC, PTR allows real-time detection of a wide range of VOCs without the need for pre-concentration or thermal desorption steps, which is particularly useful for analyzing complex mixtures such as those emitted from wood (Taiti et al., 2017; Cappellin et al., 2012).

The study offers new insights into the identification of key emitted compounds and evaluates how different surface treatments alter the VOC emission profile and intensity, potentially affecting indoor air quality and human health, particularly in highly insulated, low-ventilation buildings. While emission intensity indicates how much VOC is released from each sample, the emission profile reveals which specific compounds dominate. This distinction is important because two wood types may emit similar total amounts of VOCs, yet their emission profiles may differ significantly, potentially including more hazardous compounds such as formaldehyde or toluene. As a result, their impact on indoor air quality and occupant health may vary considerably.

The findings of this study provide valuable insights into how commonly used indoor materials can influence air quality and human health, particularly in cold climates where buildings are

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Abbreviations: CI, Confidence Interval; CEN, European Committee for Standardization; Ci, The measured concentration in μg/m^3; GC, Gas Chromatography; HCA, Hierarchical Clustering Analysis; IAQ, Indoor Air Quality; ISO, International Organization for Standardization; LCI, Lowest concentration of Interest; LCU, Liquid Calibration Unit; m/z, Mass-to-Charge Ratio; PCA, Principal Component Analysis; PTR-TOF-MS, Proton Transfer Reaction-Time of Flight-Mass Spectrometry; RH, Relative Humidity; RRID, Research Resource Identifier; TI, Tentative Identification; TVOC, Total Volatile Organic Compounds; TVVOC, Total Very Volatile Organic Compounds; VOCs, Volatile Organic Compounds; TVOC + TVVOC, The sum of the TVOC and TVVOC.

TABLE 1 The characterization of wood samples collected at Bergene Holm AS.

No	Wood species	*Botanical name*	Treatment	Comment
1	Scotch Pine	*Pinus silvestris*	Untreated	Jämtland, Sweden. Milled 18 June 2024
2	Scotch Pine	*Pinus silvestris*	Staining of No.1	Jämtland, Sweden. Milled 18 June 2024
3	Scotch Pine	*Pinus silvestris*	White glaze	Jämtland, Sweden. Samples from shelf
4	Scotch Pine	*Pinus silvestris*	White painted	Jämtland, Sweden. Samples from shelf
5	Norway Spruce	*Picea abies*	Untreated	Østerdalen, Norway, Samples from shelf
7	Norway Spruce	*Picea abies*	Stain	Østerdalen, Norway, Samples from shelf
10	Norway Spruce	*Picea abies*	White glaze	Østerdalen, Norway, Samples from shelf
11	Oak	*Quercus alba*	Untreated	North America
12	Aspen	*Populus tremula*	Untreated	-

Comments: Lumber production: Middle part of the trunk, heartwood, excluding the pith.
Artificial drying: Dried at 65°C, reducing moisture content from 55% to 14%.
During surface treatment: wood temperature 30–33°C. The wood temperature never was above 33°C.
Surface treatment: Beis: Sanding, Beis application, UV, drying, hot air drying (%0°C), and sorting. Total process time: 7 min.
Paint: Paint: Sanding followed by the application of two layers of paint, dried using air drying, UV, drying, and hot air drying at 50°C.

highly insulated and ventilation rates are often low. The importance of selecting low-emission wood materials and understanding the role of surface treatments becomes essential for the industry to determine which of their products qualify for credits related to indoor pollution source control (Zhang et al., 2022). These results will be particularly relevant for architects, material manufacturers, building designers, and policymakers seeking to balance sustainability, aesthetics, and indoor air safety.

2 Materials and methods

VOC emissions were measured using a Proton Transfer Reaction–Time of Flight–Mass Spectrometry (PTR-TOF-MS 1000, Ionicon Analyte, Austria) instrument. Nine commercially available wood interior panels were selected for analysis from a major Norwegian producer of cladding and panels, Bergene Holm (3,270 Larvik, Norway), which processes more than 1.2 million m^3 of PEFC-certified Scandinavian timber each year. The test set included untreated and surface-treated pine and spruce—the softwoods most commonly used for Norwegian wall and ceiling cladding—as well as untreated oak and aspen mouldings. Although oak and aspen account for only about 2% of the national harvest, they are occasionally specified for decorative interior applications (Table 1). Treated versions of oak and aspen were not included, as these species are not part of the company's coated product line.

The stained pine (No. 2) was freshly stained and taken directly after staining the untreated pine (No. 1). Therefore, the pine samples before and after staining were identical, as they originated from the same piece of wood and were collected immediately after staining and drying. All boards were produced from heartwood taken from the middle section of the trunk. While the logs originated from different Scandinavian growing regions, the geographic source was not controlled. Variations in a tree part (Adamová et al., 2020), climate, forestry practices (Kipping et al., 2022), and soil composition (Zhang-Turpeinen et al., 2020) may therefore contribute modestly to the emission variability. Three industrial surface treatments, such as staining (referred to as *Beis* in Norwegian), glazing (*Lasert*), and painting, were included in the pine samples. For spruce, only stained and glazed treatments were available. These treatments reflect typical finishing practices used in both residential and public buildings. All finishes were applied by the manufacturer (Bergene Holm AS), rather than in the laboratory, ensuring that the tested materials represent actual end-use products as sold and used by consumers. By focusing on real, market-ready materials rather than fresh or lab-prepared samples, this study offers a practical and applicable perspective on VOC emissions from interior wood panels already in widespread use. This approach enhances the relevance of the findings to real-world indoor air quality and material selection.

The "Beis" treatment used in this study was a water-dilutable, penetrating wood stain designed to enhance the natural grain while providing uniform coloration. According to the safety data sheet, the product includes low levels of solvents and additives such as UV stabilizers and preservatives. The "Lasert" treatment was applied using a semi-transparent, water-based wax glaze. This type of finish typically contains small amounts of solvents and additives to enhance spreadability, surface appearance, and durability. It is formulated to modify surface texture and reflectance while preserving the visibility of the underlying wood grain. The "Painted" panels were coated with a UV-curable, white-pigmented, water-based acrylic topcoat. This type of industrial finish typically contains a combination of reactive binders, low levels of solvents to adjust flow and viscosity, and photoinitiators that enable rapid polymerization under UV light. Samples were collected directly from a wood manufacturer, stored in zip-seal bags, and refrigerated

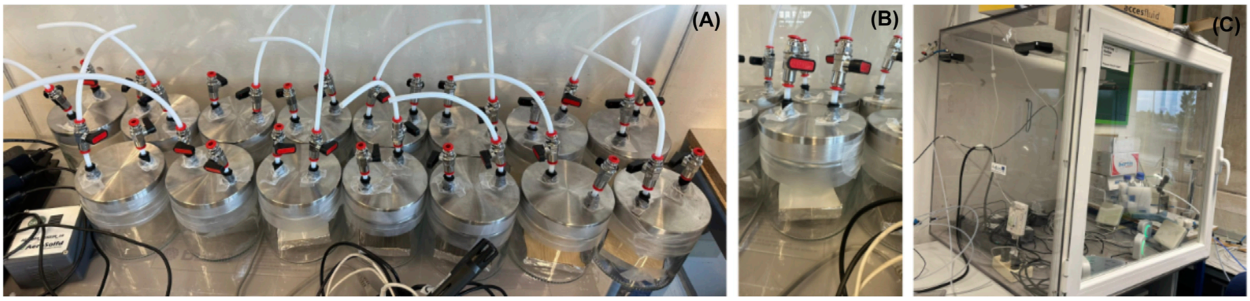

FIGURE 1
(A) Experimental setup with multiple sample chambers. **(B)** Climate-controlled chamber. **(C)** Close-up view of sample chambers and tubing configuration.

(+3 °C) for a maximum of 2 months prior to analysis. For each species, a 70 × 70 × 10 mm sample was cut using a saw. The surface intended for indoor exposure was not cut or cleaved. The exposed area was carefully selected to be free from cracks or knots to ensure surface uniformity and minimize variability in VOC emissions. All other surfaces were sealed using emission-free aluminum tape to ensure that emissions originated solely from the intended exposed surface. Each sample was placed inside a sealed 0.98 L glass chamber equipped with inlet and outlet Teflon tubes, establishing a controlled loading rate of 5 m^2/m^3, based on the sample area and chamber volume (Figure 1). The inlet and outlet were connected to a PTR-TOF-MS system for real-time VOC monitoring. Teflon tubing was selected due to its chemical inertness and widespread use in VOC sampling systems, with studies indicating minimal interaction with most VOCs (Morris et al., 2024; Deming et al., 2019). Although some uncertainty remains regarding the degree to which Teflon may adsorb or retain highly volatile compounds, its impact is generally considered negligible for short-term measurements.

To control background emissions and potential contamination from the experimental setup, two blank chambers were prepared: one containing only aluminum tape and another left completely empty. These blanks accounted for emissions from chamber materials, sealing elements, and tubing. VOC signals from these reference chambers were used for background correction by subtracting them from the corresponding sample measurements, ensuring that the reported emissions reflected only those released from the wood surfaces.

Before sampling, all chambers were cleaned with acetone, flushed with zero air for 24 h, and checked for air leaks. Background VOC levels were verified using PTR-TOF-MS, and values below 10 ppb were considered acceptable. The chambers were placed inside a 1 m^3 climate-controlled chamber maintained at 25°C ± 1°C and 50% ± 5% relative humidity. Temperature and relative humidity (RH) were continuously monitored by a sensor inside the 1 m^3 chamber. VOC concentrations were measured at three time points: 3–4, 6–7, and 14 days. Two replicates per species were analyzed.

As PTR measures a wide range of organic compounds, the detected molecules were categorized into distinct groups to facilitate a more accurate and detailed analysis. These groups include Very Volatile Organic Compounds (VVOCs) and Volatile Organic Compounds (VOCs), following the EN 16516 classification (EN16516, 2020). According to EN 16516:2017 + A1:2020 (E), "VVOCs are organic compounds that elute before n-hexane on a gas chromatographic-specific column, excluding all compounds listed in Annex G of the standard." (EN16516, 2020, p.14). VOCs, on the other hand, are defined as "compounds eluting between and including n-hexane and n-hexadecane on a gas chromatographic-specific column, including all compounds listed in Annex G." (EN16516, 2020, p.14). Under this European standard, total VOCs (TVOCs) are calculated by summing every individual VOC compound with a concentration exceeding 5 μg/m^3 (EN16516, 2020). This categorization allows for a clearer interpretation of the differences in emissions between wood types and treatments.

2.1 Proton transfer reaction- mass spectrometer

A Proton-Transfer-Reaction Mass Spectrometer [PTR-MS 1000, RRID: SCR_026459, (Ionicon, 2025)] was employed for the online monitoring of VOCs emitted from wood samples, with a detection range in parts per billion (ppb). The instrument, located at the *CARTIF* research center (Parque Tecnologico de Boecillo, Valladolid, Spain), was operated under standard conditions: drift-tube temperature of 80°C, drift-tube pressure of 3.00 mbar, and drift-tube voltage of 720 V.

The chambers were operated under static conditions without active ventilation. Air samples from the chamber headspace were drawn directly into the PTR-MS instrument via a needle, using a sampling flow rate of 60–100 sccm through the bottle inlet for 3 min. Since the chambers were fully sealed and operated without continuous purging or ventilation, there was effectively zero dilution of the headspace. VOCs emitted by the samples accumulated until equilibrium was reached, and the PTR-TOF-MS simply drew down a small, negligible fraction of that headspace for analysis. VOC concentrations were reported in μg/m^3 after conversion from ppb, but were not expressed as surface area-specific emission rates (e.g., μg/m^2·h) due to the absence of controlled air exchange within the chambers. The fundamental principles of PTR-MS operation are detailed in Schallhart (2017).

A single external acetone standard was used to derive sensitivities, provided by the IONICON Liquid Calibration Unit

(LCU). Mass-axis stability was monitored using the centroid positions of H_3O^+ (m/z 19.018) and protonated acetone (m/z 59.049), and remained within ±3 ppm throughout the experiment. Previous studies confirm that this level of stability is sufficient for chemically diverse VOCs. For instance, Cappellin et al. (2010) showed that with drift ≤5 ppm, a single-acetone calibration reproduces terpene, aromatic, and aldehyde sensitivities within ±10%. Similarly, Jensen et al. (2023) reported similar accuracy (1% ± 8%) using 2-hourly acetone injections and a kinetic transfer function. Park et al. (2013), by comparing an acetone-only calibrated PTR-TOF-MS with a fully multipoint-calibrated quadrupole PTR-MS over a month-long field campaign, found that mixing ratios and fluxes for methanol and acetone agreed within 5%, with regression slopes of 0.99–1.05 over twelve consecutive days. As the analysis is limited to relative differences among panels, the acetone-only calibration is judged to provide sufficient quantitative accuracy and to preserve strict internal comparability.

The raw data obtained from the *PTR-MS* were analyzed using the Ionicon Data Analyzer software (Ionicon PTR-TOF Data Analyzer, RRID: SCR_026458). This software automatically applies corrections for the sampling duty cycle, which varies depending on the mass-to-charge ratio (m/z) (Müller et al., 2013). For accurate mass axis calibration and reference peak shape determination, (Müller et al., 2013), two specific ion signals from the raw spectra were used following standard PTR-MS calibration protocols: m/z 157.15 ($(C_{10}H_{20}O)H^+$, Tentative Identification (TI: Decanal) for calibrating the higher m/z range, and m/z 45.034 ($(C_2H_4O)H^+$, TI: Acetaldehyde) for calibrating the lower m/z range (Müller et al., 2013). These compounds were chosen because they were consistently detected in the emission spectra of the wood panel samples, with sufficient signal intensity and well-resolved peak shapes.

In PTR-TOF-MS, mass-axis calibration requires stable and clearly defined ion peaks within the actual measurement data, as external reference ions are not added. Therefore, calibration compounds must be naturally present in the sample headspace. The calibration process aligns the mass scale and defines peak resolution but does not affect the quantitative signal or bias the analysis of the selected ions. A more detailed description of the calibration procedure can be found in Cappellin et al. (2011).

Raw data were based on their *m/z* values. To identify VOCs, a master compound assignment guide, *GLOVOCS* (freely accessible at http://glovocs.creaf.cat), was employed (Yáñez-Serrano et al., 2021). However, some detected compounds could not be fully confirmed with reference standards due to sharing the same molecular formula but differing in structural arrangement. Therefore, they were tentatively identified (TI) based on their m/z values. For example, the compound at m/z 137.132 was tentatively identified as a monoterpene. The selection of representative compounds was guided by Taiti et al. (2015). In cases where detected m/z signals could not be confidently assigned to a unique compound due to overlapping molecular formulas and similar protonated masses (e.g., within ±0.05 Da), the corresponding peaks were excluded from the reported results. For instance, the peak at m/z 138.14 (H^+) could correspond to multiple candidate compounds listed in the GLOVOCS library, each with protonated masses too close to be resolved with certainty. To preserve the accuracy of compound identification, only VOCs with unambiguous protonated masses and consistent library matches were included in the analysis. The notation (H^+) indicates the addition of one proton to the neutral molecule during ionization with H_3O^+ in the PTR-MS system.

2.2 Data analysis

The dataset (Ghaffari Jabbari et al., 2025) was analyzed using the R programming language (version 2024.12.1 + 563, RRID: SCR_000432). A descriptive analysis was carried out to evaluate the emission patterns and intensity of wood samples. Due to the limited number of groups and small sample sizes per group, this study employed pairwise comparisons of posterior distributions, a method suitable for groups with as few as two samples. Each group (k) (e.g., a specific wood species or surface treatment) had its mean emission value μ_k described by a posterior t-distribution, estimated from the observed data. To compare emission levels between two different groups, we denoted their means as μi *and* μj, where i and j index distinct groups (e.g., species A vs. species B). These means were treated as stochastic variables, and the probability $p = min\,\{P(\mu_i < \mu_j), P(\mu_j < \mu_i)\}$ was used to assess whether a significant difference existed. If this probability fell below a predefined threshold, the groups were considered to differ significantly. This approach enabled robust group comparisons even with small sample sizes. This method is detailed in Nyberg (2018). Principal Component Analysis (PCA) was employed to characterize the emission profiles of the wood samples and to identify VOCs associated with specific treatments, even if they were not the dominant contributors to emissions. Hierarchical Clustering Analysis (HCA) was used to group wood samples based on their VOC emission profiles, revealing patterns and similarities among different treatments and wood types.

3 Results and discusion

3.1 Emission intensity

3.1.1 Untreated wood samples

In the current trial, more than 77 mass peaks were detected in the m/z range of 50–250. The primary results were reported in parts per billion (ppb) for a loading rate of 5 m^2/m^3. To facilitate comparison with other studies, the results were normalized to a standard loading rate of 1 m^2/m^3 by dividing all concentrations by 5, allowing for consistent interpretation across studies using different loading factors. However, due to the absence of controlled air exchange, surface area-specific emission rates (e.g., $\mu g/m^2 \cdot h$) could not be calculated. To express VOC concentrations in $\mu g/m^3$, the ppb values were converted using the ideal gas law, applying Equation 1 under standard conditions of 25°C and 1 atm (Spellman, 2017).

$$\mu g/m^3 = \frac{MW}{24.45} \times ppb \tag{1}$$

Where:

$\mu g/m^3$ = VOC concentration in micrograms per cubic meter.
ppb = Concentration in parts per billion by volume.
MW = Molecular weight of the compound (g/mol).

The results indicate that, among the untreated wood samples, total emissions from pine and oak were higher than those from other

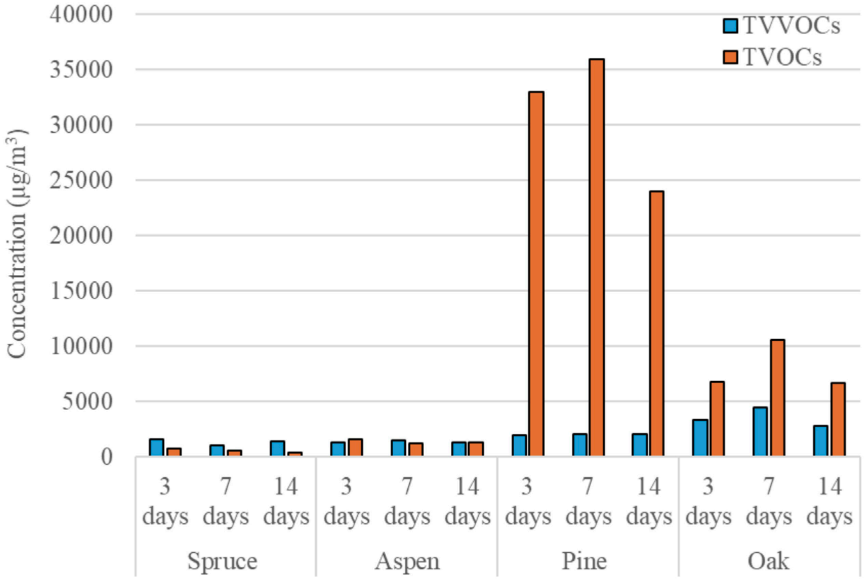

FIGURE 2
Total VOCs and VVOCs emitted by untreated wood samples measured over 3, 7, and 14 days.

wood types. Oak exhibited the highest VVOC emissions, while pine showed the highest TVOC emissions. After 7 days, VOCs accounted for 94% of the total emissions (VVOCs and VOCs) from pine and 70% from oak. In contrast, 65% of the total emissions from spruce were VVOCs. Aspen exhibited a more balanced distribution, with VVOCs and VOCs accounting for 54% and 46% of total emissions, respectively (Figure 2).

Pairwise comparison analysis revealed a significant difference in TVVOCs between oak and spruce (mean difference: 1865 µg/m^3; 95% CI: 47–3,683 µg/m^3, $p < 0.05$). For TVOCs, significant differences were observed between pine and all other wood samples, with mean differences ranging from 29,828 to 35,336 µg/m^3 ($p < 0.05$). Additionally, significant differences were found between oak and spruce (mean difference: 5,508 µg/m^3; 95% CI: 4,122–6,895 µg/m^3, $p < 0.05$), and between oak and aspen (mean difference: 4,789 µg/m^3; 95% CI: 1780–7,798 µg/m^3, $p < 0.05$). No statistically significant differences were found among the other wood types in terms of their TVOC emissions ($p > 0.05$). Table 2 presents the relative contributions of VVOCs and VOCs to the total measured emissions for each wood type based on quantitative intensity data. Figures 3, 4 present the distribution of VVOCs and VOCs across untreated wood samples after 7 days, respectively.

The results show that untreated pine has high emissions of C_3H_6O (Tentatively identified (TI): acetone, 36%), and C_5H_6 (TI: terpene fragment, 16%), and CH_4O (TI: methanol, 9%), which is aligned with the results of Skulberg et al. (2019). In contrast, untreated spruce had generally low emissions, except for C_3H_6O (TI: acetone, 35%) and CH_4O (TI: methanol, 30%). Aspen exhibits moderate emissions with CH_2O (TI: formaldehyde, 27%) and CH_4O (TI: methanol, 21%), while oak shows high formaldehyde emissions (25%) and C_2H_2O (TI: ketene, 57%). Due to the wide variety of VOCs, they are categorized into five main groups: terpenes (C_nH_m), miscellaneous hydrocarbons (C_nH_m), oxygenated compounds ($C_nH_mO_t$), nitrogen-containing compounds ($C_nH_mN_k$), and sulfur-containing compounds ($C_nH_mS_x$). Compounds containing both oxygen and nitrogen are classified under oxygenated compounds. The results show that hydrocarbons are the dominant VOC group emitted from spruce, aspen, and especially pine. This would agree with previous studies that showed terpenes as one of the most abundant VOCs emitted by wood (Taiti et al., 2017; Risholm-Sundman et al., 1998; Courtois et al., 2009). In contrast, oxygenated compounds are the most prominent group in oak. Unlike the others, pine also showed a notable presence of nitrogen-containing compounds. Untreated pine emitted high levels of C_6H_8 (TI: terpenes fragment, 26%), $C_{10}H_{16}$ (TI: monoterpenes, 18%), C_7H_{10} (TI: terpene fragment, 15%), C_6H_9 (TI: cyclopentenyl carbenium, 14%), and C_7H_8 (TI: toluene, 11%), reflecting its resinous nature (Schumann et al., 2012). Oak showed high emissions of $C_2H_4O_2$ (TI: acetates, 48%), $C_{10}H_{16}$ (TI: monoterpenes, 26%), and C_6H_8 (TI: terpenes fragment, 20%). Untreated aspen and spruce had relatively moderate emissions, with notable contributions from $C_2H_4O_2$(TI: acetates, 28%, 16%), C_6H_{10} (TI: hexenol fragment 29%, 25%), $C_{10}H_{16}$ (TI: monoterpenes, 19%, 23%), and C_6H_8 (TI: terpene fragment, 13%, 23%), respectively (Table 2). The prevalence of acetates, hexenol fragments and residual terpenes in the untreated samples is consistent with, as these compounds lie along the same oxidative trajectory: fresh softwood extractives are initially rich in terpenes, which oxidize to unsaturated alcohols (e.g., hexenol), and subsequently to aldehydes and carboxylic acids (e.g., hexanal, acetic acid), which Hyttinen identified as dominant emissions in both aged air-dried and heat-treated wood.

To evaluate the potential health implications of these emissions, measured concentrations were compared with the corresponding Lowest Concentration of Interest (LCI) thresholds, where available, as reported by the European Commission (2023). Using the substance-specific LCI of 2,500 µg/m^3 for the principal

TABLE 2 The emission profile and emission intensity of wood samples.

Wood pane	Emission profile		Emission intensity			
	VVOC	VOC	VVOC	*Ci/LCI*	VOC	*Ci/LCI*
Untreated pine	Terpene frag	Terpenes	Acetone, 35%	0.01	terpenes frag., 26%	N/A
		Benzene	Terpene frag., 16%	N/A	Monoterpenes, 18%	1.7
		Toluene	Methanol, 8%	N/A	Terpene frag., 15%	N/A
		Cyclopentenyl carbenium	Alkyl frag. 8%	N/A	Cyclopentenyl carbenium, 14%	N/A
					Toluene, 11%	0.9
Stained Pine	Isoprene frag	Butanone	Acetone, 27%	0.02	Terpenes frag., 32%	N/A
	Alkyl frag	Hexenol frag	Aldehydes frag., 15%	N/A	Monoterpenes, 30%	1
	Acetaldehyde	Heptanal	Methanol, 12%	N/A		
	Aldehydes frag	Pentanal	Isoprene, 14%	N/A		
	Acetone	Alkyl frag				
	Methanol					
Glazed pine	Balanced	Acetates	Acetone, 23%	0.004	Monoterpenes, 40%	0.8
			Aldehydes frag., 18%	N/A	Terpenes frag., 36%	N/A
			Methanol, 17%	N/A		
			Isoprene, 12%	N/A		
Painted pine	Nitromethane	Balanced	Methanol, 19%	N/A	Monoterpenes, 34%	0.1
			Ketene, 16%	N/A	Terpenes frag., 30%	N/A
			Aldehydes frag., 14%	N/A		
Untreated spruce	Isoprene fragment	Balanced	Acetone, 35%	0.003	Hexenol frag.25%	0.1
	Acetone		Methanol, 30%	N/A	Terpene frag., 23%	N/A
			Aldehydes frag., 9%	N/A	Monoterpenes, 23%	0.05
			Ketene, 7%	N/A	Acetates, 16%	0.07
			Acetaldehyde, 6%	0.21		
Stained spruce	Alkyl frag	Butanone	Methanol,39%	N/A	Butanone, 22%	0.01
			Acetone,15%	0.001	Trepens frag., 22%	N/A
			Ketene, 12%	N/A	Monotrepens, 21%	0.05
					Hexenol frag., 19%	0.05
Glazed spruce	Methanol	Propanoates	Methanol, 82%	N/A	Monoterepens, 23%	0.1
	Ketene	Terpenes			Trepens frag., 21%	N/A
	Formaldehyde				Hexenol frag.,21%	0.07
	Alkyl frag				Acetates, 15%	0.08
	Formic acid					

(Continued on the following page)

TABLE 2 (*Continued*) The emission profile and emission intensity of wood samples.

Wood pane	Emission profile		Emission intensity			
	VVOC	VOC	VVOC	*Ci/LCI*	VOC	*Ci/LCI*
Oak	Formaldehyde	Butanone	Ketene, 57%	N/A	Acetates, 48%	2.45
	Ketene	Acetates	Formaldehyde, 26%	6.74	Monoterpenes, 26%	0.6
		Alkyl frag			Terpenes frag., 20%	N/A
Aspen	Methanol	Hexenol frag	Formaldehyde, 27%	4.08	Hexenol frag.29%	0.17
	Aldehydes frag		Methanol, 21%	N/A	Acetates, 28%	0.29
	Alcohol frag		Aldehydes frag. 13%	N/A	Monoterpenes, 19%	0.1
			Ketene, 11%	N/A	Terpene frag., 13%	N/A

monoterpenes ($C_{10}H_{16}$), only untreated fresh pine exceeded this limit ($C_i/LCI = 1.7$), suggesting potential concerns during the early installation phase in low-ventilation conditions. Similarly, oak exceeded the LCI values for both acetate ($C_i/LCI = 2.45$) and formaldehyde ($C_i/LCI = 6.74$), while aspen exceeded the limit for formaldehyde ($C_i/LCI = 4.08$). Although the experiments were conducted under static, non-ventilated conditions to simulate worst-case indoor exposure, these exceedances underline the importance of material selection and the need for adequate ventilation during and immediately after installation.

In contrast, all other compounds for which LCI values were available remained well below their respective thresholds across all samples. This suggests that, despite the static test conditions, most individual compounds do not pose a significant health risk based on LCI criteria.

The overall results indicate that emission intensity is strongly influenced by wood type. While spruce emissions were predominantly composed of VVOCs such as methanol, pine and oak primarily emitted VOCs. Among the wood types, pine exhibited the highest total VOC emissions, dominated by terpenes and aromatic compounds, whereas oak showed the highest total VVOC emissions. These findings align with those of Kovačević et al. (2023), who reported a significant difference in TVOC emissions between pine and spruce. Specifically, pine's dominant VVOC was methanol (~35%), followed by terpene fragments (26%). Oak primarily emitted ketene (VVOC, 54%) and acetates (VOC, 48%), spruce emitted mainly acetone (VVOC, 35%) and hexanol (VOC, 25%), and aspen emitted formaldehyde (VVOC, 27%) and hexanol (VOC, 29%). These findings reinforce that both emission intensity and composition are species dependent.

3.1.2 Effect of treatment on emission intensity

Figure 5 illustrates the total VVOC and VOC emissions of treated pine and spruce samples. Regarding TVVOC among the pine samples, stained pine exhibited the highest TVVOC emissions, with a statistically significant increase of approximately 63% compared to untreated pine (mean difference: 3,537 $\mu g/m^3$; 95% CI: 51–7,127 $\mu g/m^3$, $p < 0.05$). It also showed significant differences compared to other treated pine samples, with mean differences of 3,910 and 4,450 $\mu g/m^3$ relative to glazed pine and painted pine, respectively (95% CI, $p < 0.05$). No significant differences were observed between other treated pine samples and untreated pine ($p > 0.05$). In contrast, TVOC emissions were significantly lower in all treated pine samples compared to untreated pine. The three mean reductions in TVOC emissions were in the range of 26,614–33,449 $\mu g/m^3$, all of them with statistically significant differences from zero ($p < 0.05$). For spruce samples, a significant difference was observed only between glazed spruce and both stained and untreated spruce. The mean differences were 3,368 $\mu g/m^3$ compared to stained spruce and 2,951 $\mu g/m^3$ compared to untreated spruce (95% CI, $p < 0.05$). In contrast, TVOC emissions in spruce remained relatively stable, with no statistically significant differences observed among the spruce samples ($p > 0.05$). Table 3 summarizes the percentage variation in emission intensity for pine and spruce following treatment. Glazing reduced total emissions (TVOC + TVVOC) from pine by 81% but increased total emissions (TVOC + TVVOC) from spruce by 65%. Similarly, staining modified pine's emission pattern increased VVOC emissions by 63% while reducing VOC emissions by 74%. These results are consistent with findings by Hyttinen et al. (2010), and Romano et al. (2022), which demonstrated that treatments have a variable impact on VOC emissions.

Figure 6 shows that the stained treatment increased the concentration of the main emitted VVOCs from pine, except for C_5H_6 (TI: terpene fragment), resulting in a significant difference between stained and the other pine samples. All treatments reduced the concentration of C_5H_6. Figure 7 illustrates that the overall reduction in the concentration of major VOC contributors emitted by untreated pine led to significant differences in VOC levels between untreated and treated pine samples. The most notable reductions were observed in C_6H_8 (TI: terpene fragment), $C_{10}H_{16}$ (TI: monoterpenes), C_7H_{10} (TI: terpene fragment), C_6H_9 (TI: cyclopentenyl carbenium), and C_7H_8 (TI: toluene). However, all three treatments led to an increase in C_6H_{10} (TI: hexenol fragment), and stained pine also showed an increased concentration of C_4H_8O (TI: butanone).

When the concentrations are normalised to their substance-specific EU-LCI values, all *Ci/LCI* ratios fall below the respective

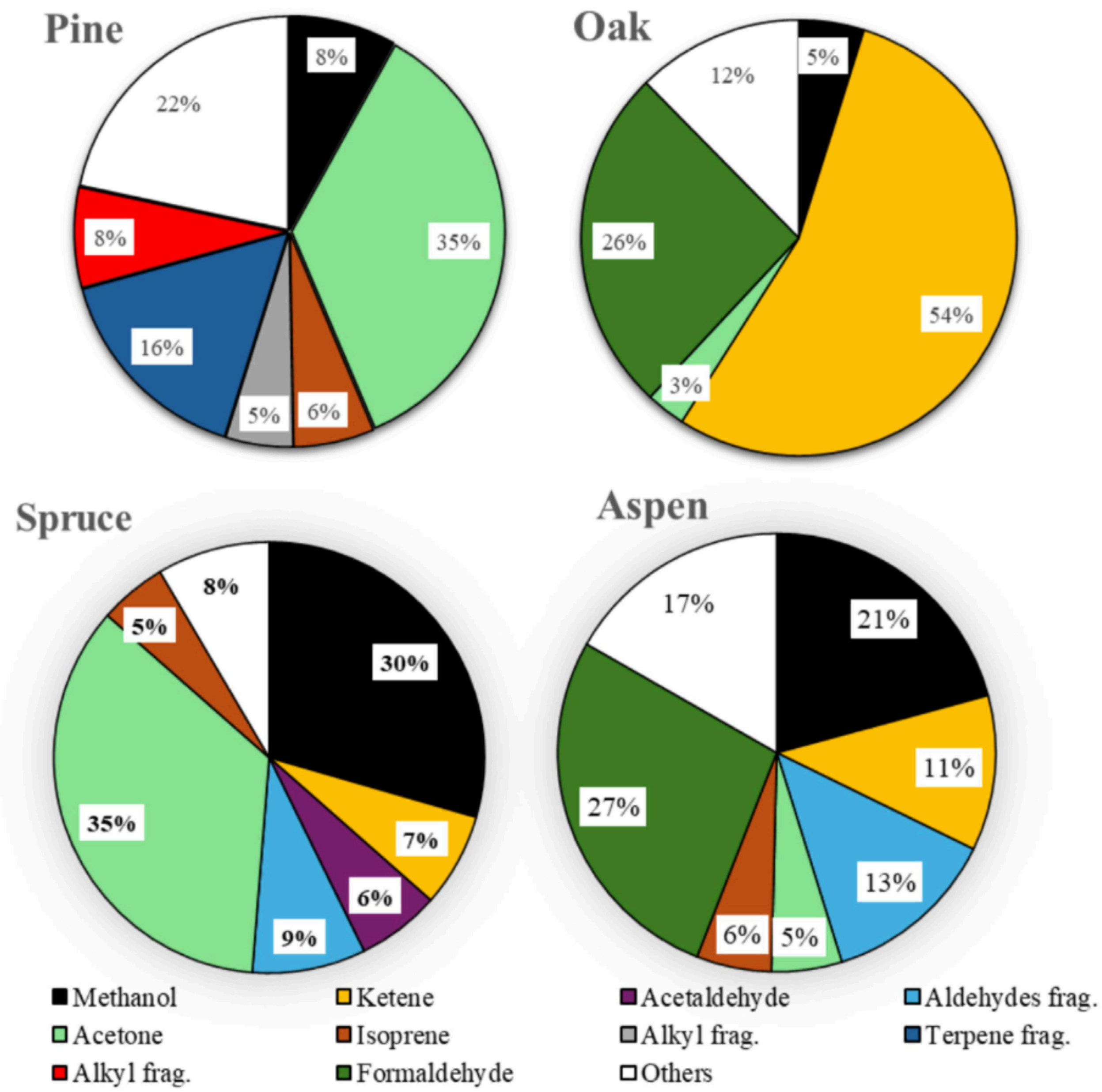

FIGURE 3
VVOC emissions intensity of untreated wood samples after 7 days.

health-based thresholds except for monoterpenes ($C_{10}H_{16}$) from stained pine, which meet the limit exactly ($Ci/LCI = 1$). This shows that every surface finish substantially lowers terpene emissions and, under stagnant air conditions, keeps them within acceptable levels (Table 3).

Overall, the observed fluctuations in VOC and VVOC emissions can be primarily attributed to changes in terpenes (C_5H_6, C_5H_8, C_6H_8, C_7H_{10}, C_9H_{12}, $C_{10}H_{14}$, $C_{10}H_{16}$) and aromatic contents (C_7H_8, C_6H_6, C_7H_7). This is aligned with the results of Simon et al. (2020), which showed that the identified compounds were primarily terpenes and carbonyl. Glazing, staining, and painting reduced the terpene content in pine by approximately 71%, 52%, and 89%, respectively, and decreased aromatic compound emissions by 94%, 86%, and 97%, respectively. However, staining increased aldehyde emissions by 43%, highlighting the complex effect of surface treatments on emission composition. This variation is largely attributed to the resinous nature of pine, which makes it more chemically reactive to treatments. Some parts of these findings are in agreement with Kovačević et al. (2023), who observed a reduction in terpene content following the drying of pine. Romano et al. (2022) similarly reported that treated softwood emitted fewer terpenes, while several other VOCs were released at higher concentrations.

Figure 8 shows that the main contributor to the significant difference observed between glazed spruce and the other samples is CH_4O (TI: Methanol), with a concentration of 3,279 $\mu g/m^3$. This value is approximately 12 times higher than the concentrations

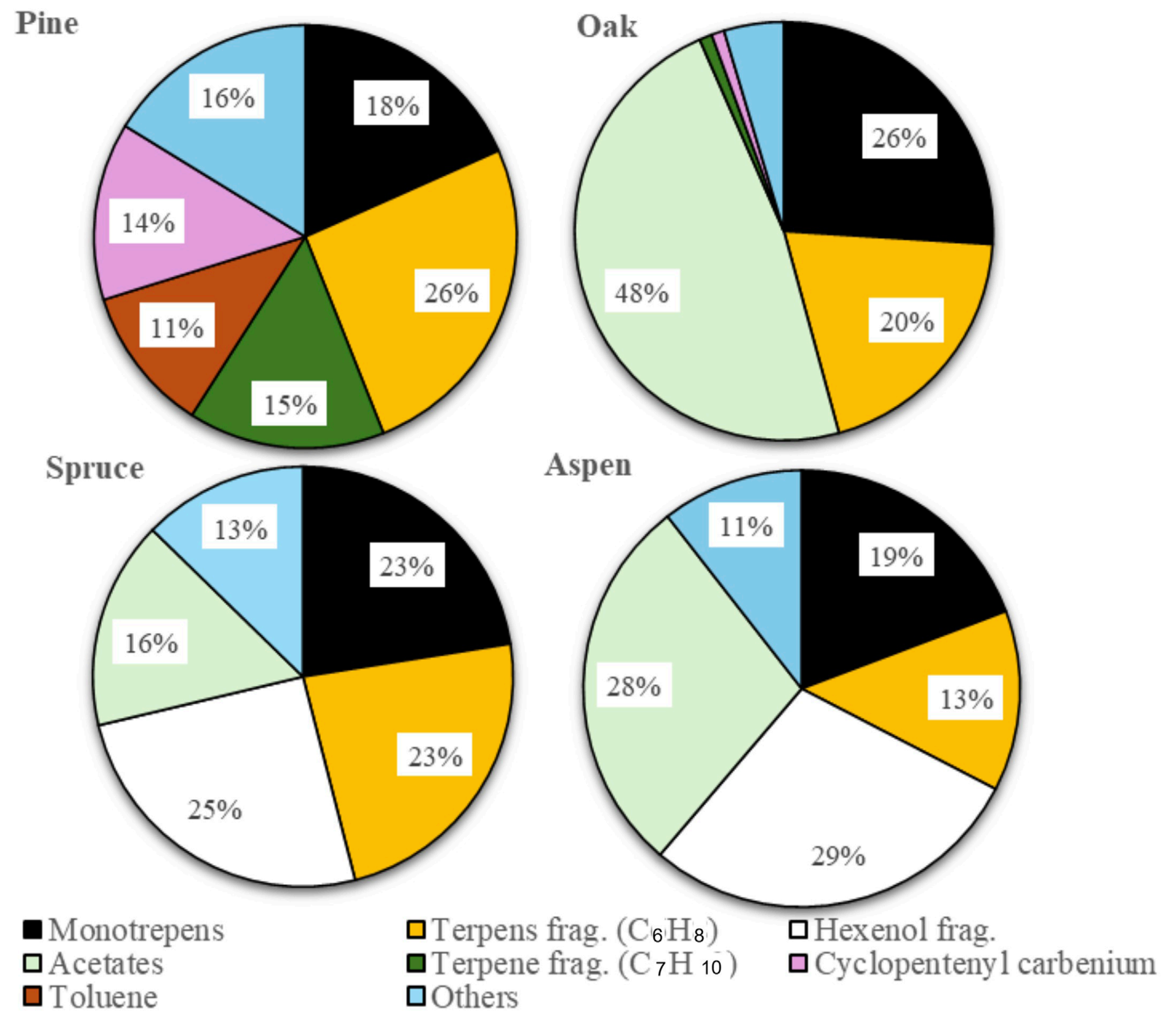

FIGURE 4
VOC emissions intensity of untreated wood samples after 7 days.

of other detected compounds, potentially indicating an outlier. Despite the use of duplicate samples and consistent environmental conditions, the observed discrepancy might be attributed to a measurement error associated with the PTR instrument. The PTR is known to be sensitive to saturation effects at high concentrations, which could lead to overestimated values if any compounds exceed the instrument's dynamic range. Therefore, the high methanol concentration could be highlighted from the experimental results. However, to confirm whether this value represents a true emission intensity, repeated measurements are necessary. The lower resin content in spruce may explain unexpected spikes, such as the elevated methanol levels in glazed spruce, which are likely due to interactions with the treatment chemistry. Overall, surface treatments had a substantial impact on emission intensity, and their effects varied depending on the untreated wood type. This study confirms that painting pine can effectively transform it from a high-emission material into a low-emission product suitable for indoor use. Conversely, staining pine introduces aldehyde emissions, which may necessitate enhanced ventilation in indoor environments.

3.2 Emission profile

3.2.1 Untreated wood samples

Figure 9 illustrates the distinct emission profiles of different untreated wood types, which are strongly influenced by wood species. Regarding VVOCs, pine stands out with emissions of terpene fragments (TI), C_3H_6O (TI: acetone), C_3H_4 and C_4H_8 (TI: alkyl fragments), and C_2H_4O (TI: acetaldehyde). In contrast, oak is associated with CH_2O (TI: formaldehyde) and C_2H_2O (TI: ketene), while aspen aligns with C_5H_{10} (TI: alcohol fragment), C_4H_6 (TI: aldehyde fragment), and CH_4O (TI: methanol). Untreated spruce, positioned centrally in the PCA plot, suggests a more balanced emission profile, lacking strong

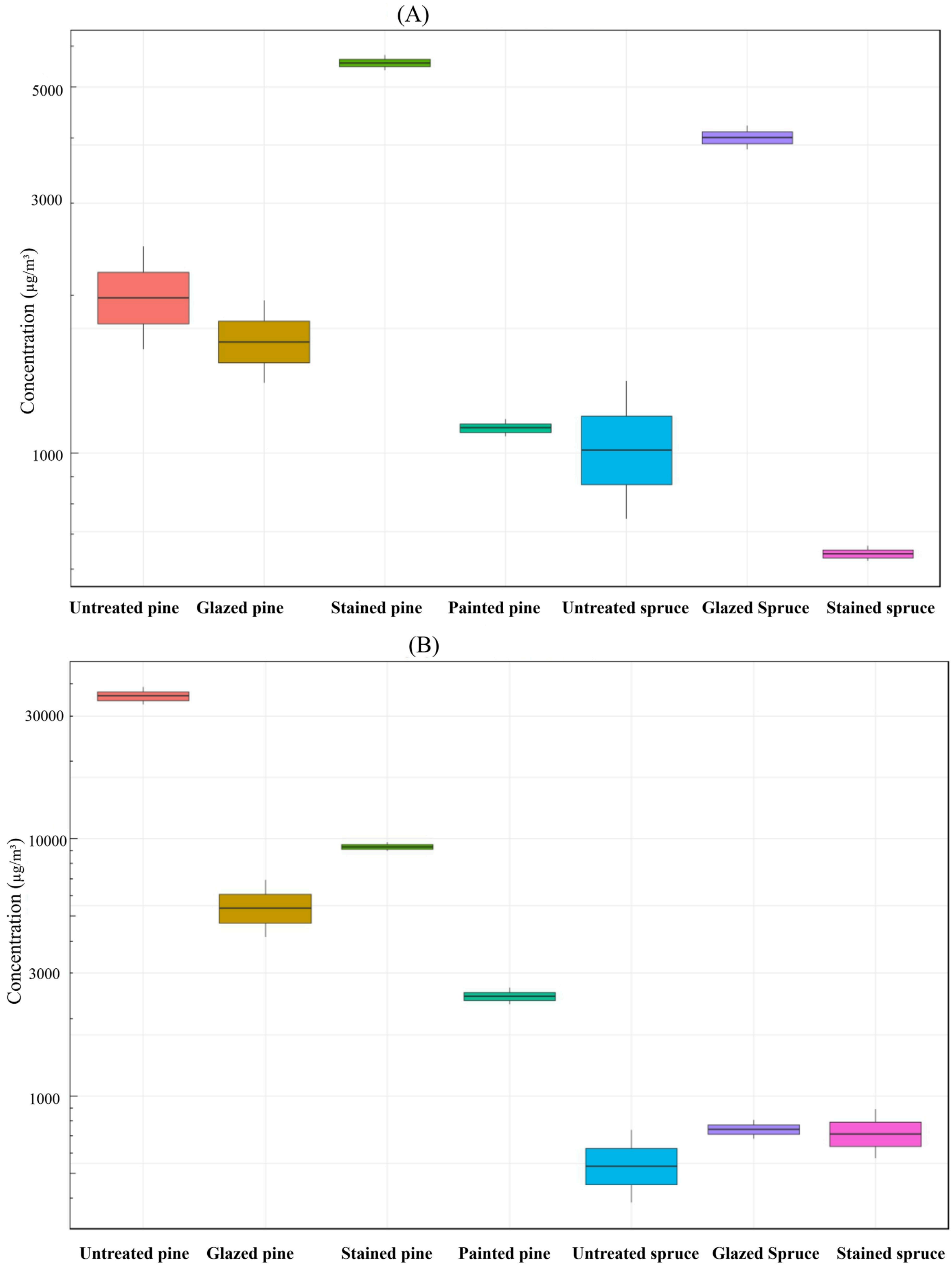

FIGURE 5
Concentration levels of total **(A)** VVOCs, **(B)** VOCs across different treatments after 7 days.

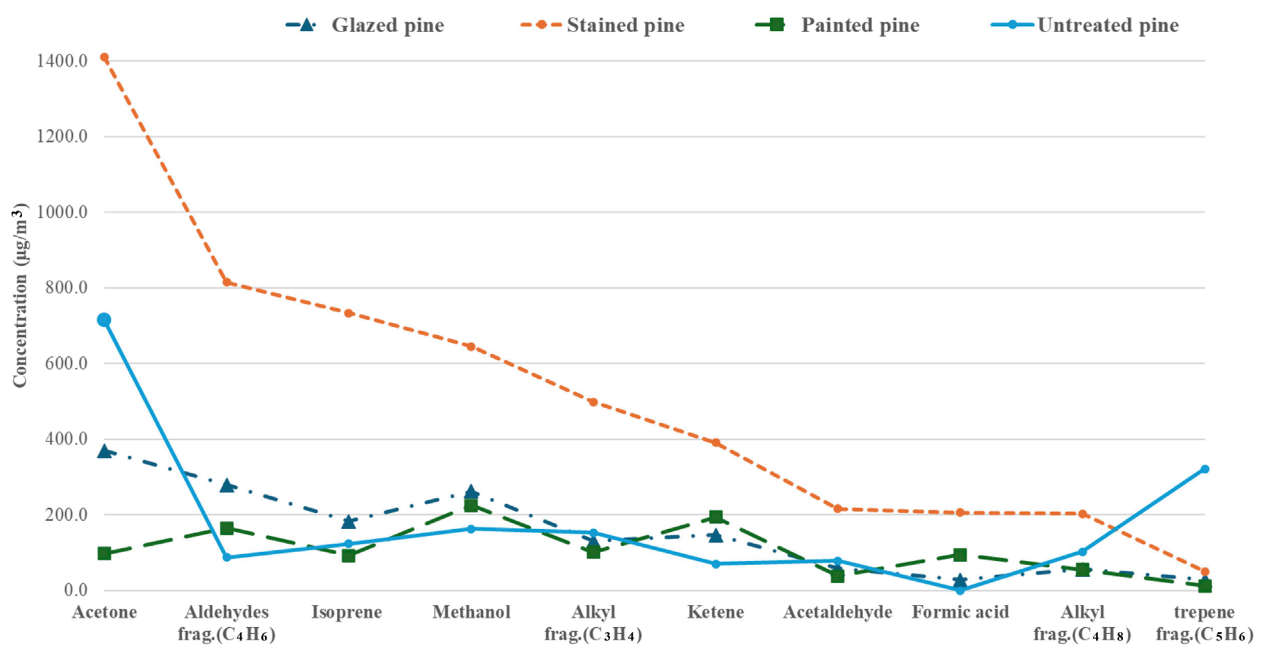

FIGURE 6
The main individual VVOCs emitted by treated and untreated pine after 7 days.

TABLE 3 The percentage of variation in the emission intensity from untreated samples after surface treatment.

Wood type	Treated type	TVVOCs	TVOCs	Total
Pine	Stained	+63%*	−74%*	−60%
	Glazed	−18%	−84%*	−81%*
	Painted	−45%	−93%*	−90%
Spruce	Stained	−39%	+23%	−15%
	Glazed	+73%*	+24%	+65%*

*Statistically significant ($p < 0.05$).

associations with specific compounds. When examining primary VOC emissions, pine's profile is predominantly characterized by terpene emissions—including monoterpenes and terpene fragments such as C_7H_{12} and C_6H_8—along with notable emissions of C_7H_8 (TI: toluene), $C_{10}H_{14}$ (TI: p-cymene), C_6H_9 (TI: cyclopentenyl carbenium), and C_6H_6 (TI: benzene). Aspen and untreated spruce are primarily associated with C_6H_{10} (TI: hexenol fragment), while oak is linked to C_4H_8O (TI: butanone), C_7H_{12} (TI: alkyl fragment), and $C_2H_4O_2$ (TI: acetates) (Table 2). Although all wood types emit many of these compounds, their distinctive emission profiles arise from differences in relative abundances, confirming the findings of Bourtsoukidis et al. (2014) regarding common oxygenated compounds from wood plant species.

3.2.2 Effect of treatment on emission profile

Figure 10 compares the VVOC emission profiles of treated and untreated pine and spruce, demonstrating that surface treatments significantly alter emission profiles. Untreated pine is characterized by emissions of C_5H_6 (TI: terpene fragment) and CH_2O (TI: formaldehyde). Upon treatment, its VVOC emission profile changed notably depending on the type of treatment applied. Fresh stained pine differs markedly from the other samples, as it is associated with a diverse range of VVOCs, particularly C_3H_2 (TI: isoprene fragment), C_4H_6 (TI: aldehydes fragment), C_3H_4, C_4H_8 (TI: alkyl fragment), C_2H_4O (TI: acetaldehyde), C_5H_8 (TI: isoprene), and CH_4O (TI: methanol). In contrast, glazed and painted pine show more balanced VVOC emission profiles, with painted pine distinctly emitting nitromethane CH_3NO_2 (TI: nitromethane). Figure 11 further reinforces the impact of treatments on the pine VOCs emission profile. While both untreated and stained pine emit $C_{10}H_{16}$ (TI: monoterpenes) and C_6H_8 (TI: terpene fragment), untreated pine is uniquely characterized by C_7H_8 (TI: toluene) and C_6H_6 (TI: benzene), $C_{10}H_{14}$ (TI: p-cymene), C_9H_{12} (TI: sesquiterpene), C_6H_9 (TI: cyclopentenyl carbenium), C_7H_{10} (TI: terpene fragment), and C_8H_8 (TI: styrene). Stained pine, however, is characterized by C_4H_8O (TI: butanone), C_6H_{10} (TI: hexanol fragment), $C_7H_{14}O$ (TI: heptanal), $C_5H_{10}O$ (TI: pentanal), and C_7H_{12} (TI: alkyl fragment). Glazed pine, positioned near the PCA origin, suggests a more balanced and less extreme VOC emission profile, primarily influenced by $C_2H_4O_2$ (TI: acetates). For spruce, untreated samples are associated with C_3H_2 (TI: isoprene fragment) and C_3H_6O (TI: acetone), while stained spruce is strongly associated with C_3H_4 (TI: alkyl fragment). Glazed spruce has a more complex emission profile, with significant contributions from CH_4O (TI: methanol) and C_2H_2O (TI: ketene), C_4H_8 (TI: alkyl fragment), CH_2O_2 (TI: formic acid), and CH_2O (TI: formaldehyde). In terms of VOC emissions, untreated and stained samples display a balanced VOC emission profile, with stained particularly distinguished by C_4H_8O (TI: butanone), and untreated spruce relatively associated with C_6H_{10}

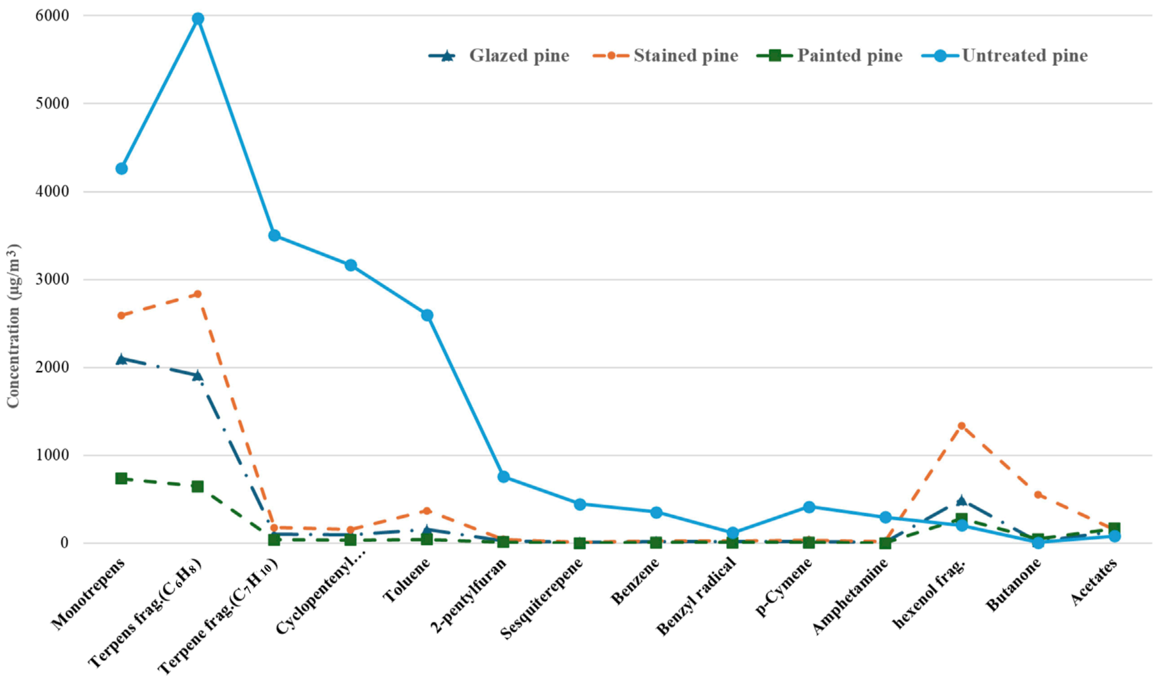

FIGURE 7
The main individual VOCs emitted by treated and untreated pine after 7 days.

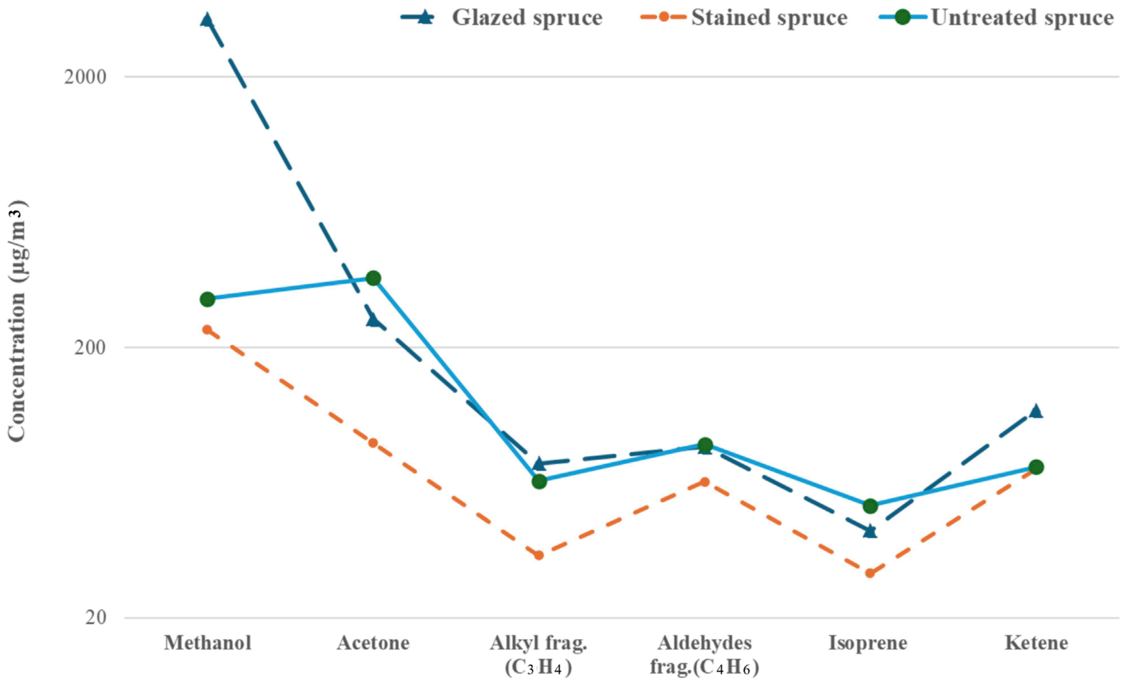

FIGURE 8
The main individual VVOCs emitted by treated and untreated spruce after 7 days.

(TI: hexenol fragment) and $C_2H_4O_2$ (TI: acetates). In contrast, glazed spruce is characterized by $C_{10}H_{16}$ (TI: monoterpenes), C_6H_8 (TI: terpene fragment), and $C_3H_6O_2$ (TI: propanoates).

Overall, surface treatments substantially modify emission profiles by suppressing or introducing specific compounds of concern. In pine, formaldehyde, terpene fragments, and aromatic

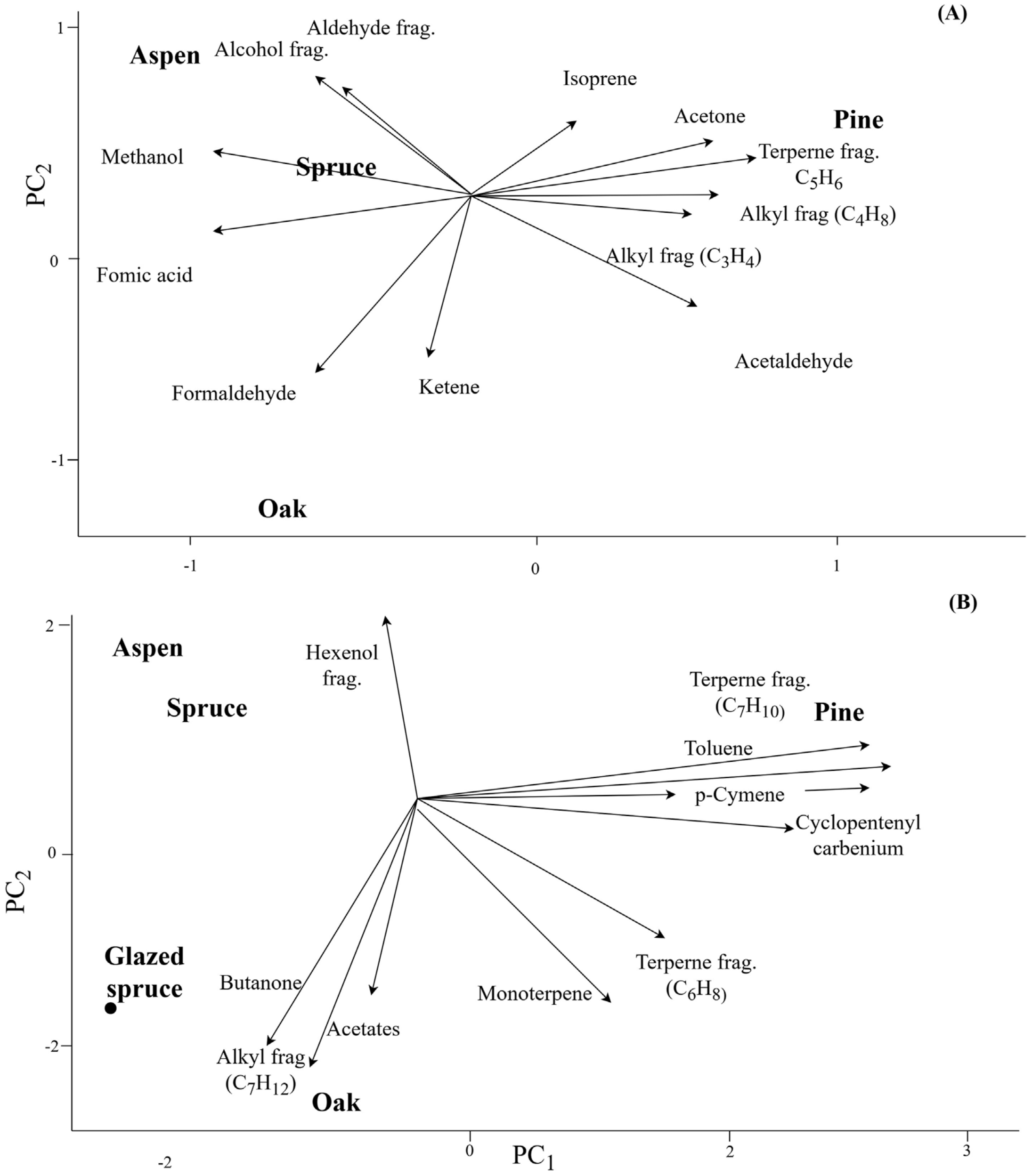

FIGURE 9
PCA biplot of **(A)** VVOC and **(B)** VOC emission profile of untreated wood samples.

hydrocarbons were key distinguishing factors between untreated and treated samples. Staining reduced these emissions while increasing the release of methanol, heptanal, pentanal, hexenol fragments, and butanone. Painting untreated pine effectively reduced hazardous emissions such as benzene and toluene, aligning its emission profile with that of lower-emitting materials like spruce and aspen. In contrast, staining increased the presence of aldehydes and introduced compounds such as acetaldehyde, butanone, and heptanal, substances linked to mucous membrane irritation and potential carcinogenic effects. Similarly, while glazing preserved the wood's natural appearance, it led to a substantial rise in methanol emissions in spruce (up to 82%), a compound known to pose neurological and respiratory risks at elevated concentrations. These findings underscore that surface treatments can either mitigate or exacerbate health-related emission risks, depending on both the wood species and the treatment chemistry. Parts of these results are consistent with those reported by Jensen et al. (2001). Table 2 presents the emission profiles of all samples, further illustrating these effects. Several of these findings align with previous studies. Risholm-Sundman et al. (1998) and Courtois et al. (2009) reported elevated terpene emissions from softwoods, particularly pine, due to their resin content. Meyer and Boehme (1997) found that green oak emitted higher levels of formaldehyde compared to pine. Jensen et al. (2001) reported that aldehydes and esters were

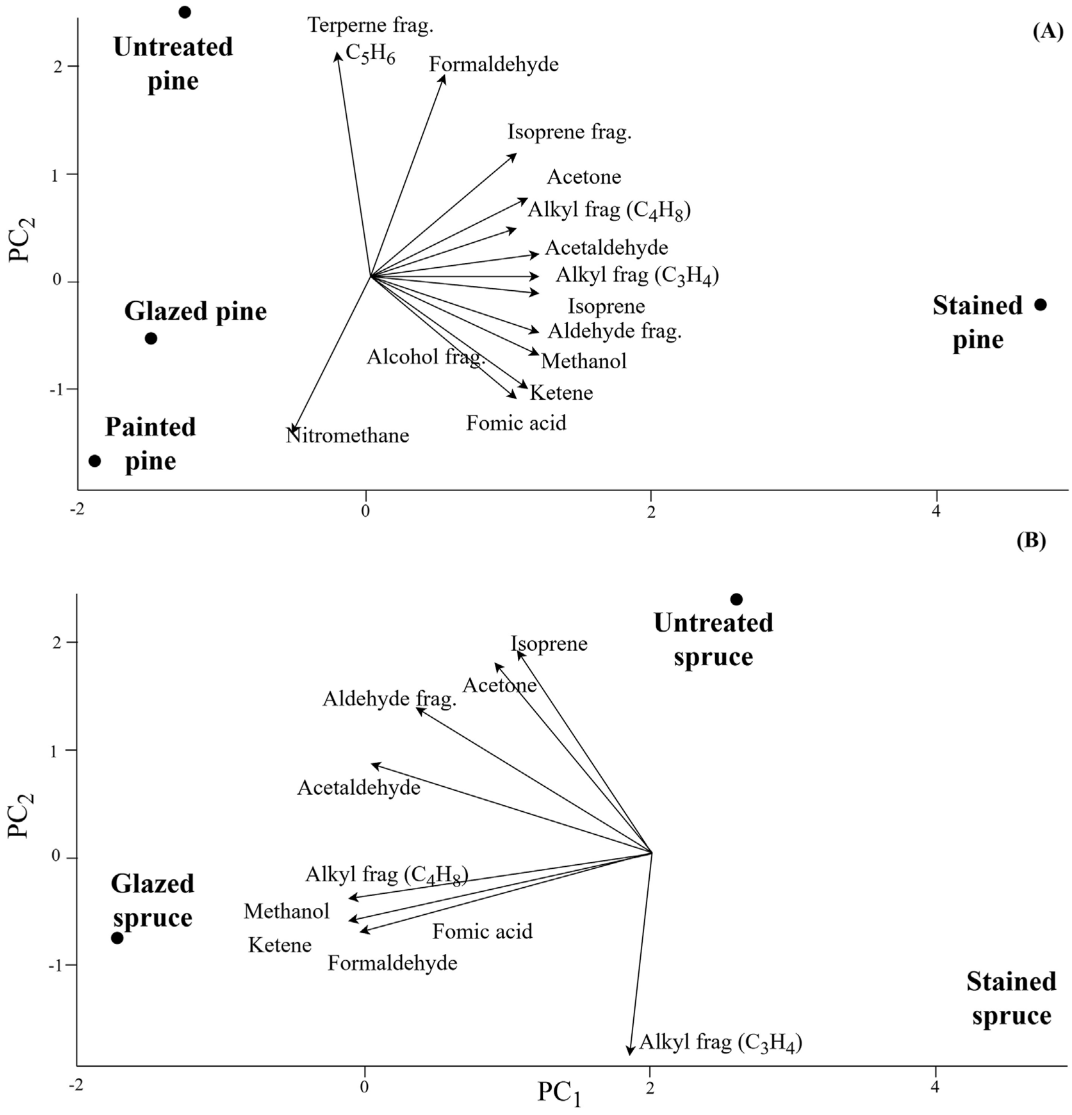

FIGURE 10
PCA biplot of VVOC emission profiles of **(A)** treated pine **(B)** treated spruce samples.

the primary compounds originating from surface-treated wood-based materials. However, while glycol ethers and esters were also identified in their study, their emissions were not observed at high levels in the present research. Alapieti et al. (2021) demonstrated that painting significantly alters the emission profile of untreated pine, a finding consistent with the present study.

3.3 Emission pattern

Hierarchical clustering analysis (HCA) was applied to explore similarities in VVOCS + VOC emissions among the samples. The data matrix consisted of log-transformed emission intensities ($\log_{10}$ [$\mu g/m^3 + 1$]) that were subsequently autoscaled (mean = 0, SD = 1). Because Euclidean distances were calculated on these scaled, but not row-normalized, values, the branch lengths in Figure 12 reflect both the presence of specific VOCs and their relative magnitudes. Samples that emit the same compounds at higher levels cluster farther apart than those with identical profiles but lower intensities.

The resulting dendrogram reveals a tight cluster of untreated pine and stained pine, indicating that the staining process shifts pine's terpene-rich spectrum without fundamentally altering its composition. In contrast, oak, aspen, untreated and treated spruce, glazed pine, and painted pine formed separate groups with varying degrees of similarity. Among them, oak remained an outlier, merging at a higher hierarchical level, suggesting that while it shares some emission characteristics with other samples, it retains a unique emission signature. Furthermore, similarity analysis between painted pine, glazed pine, and aspen revealed insightful patterns regarding the influence of surface treatments on emission profiles. Painting and glazing resulted in highly similar VOC emission patterns for pine, with both Pearson correlation (0.965) and Cosine similarity (0.975) indicating near-identical profiles. This suggests that while these treatments emit similar types of compounds,

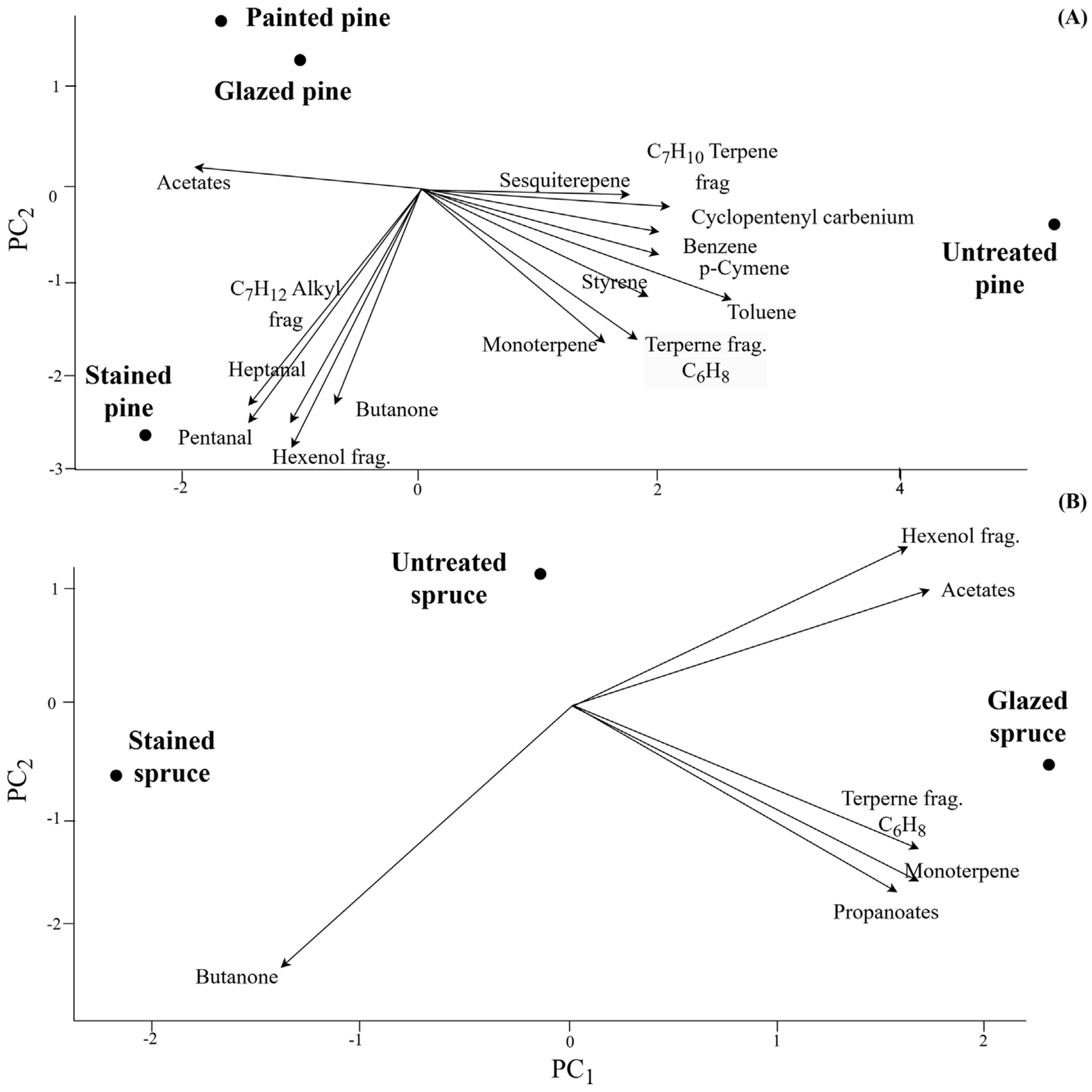

FIGURE 11
PCA biplot of VOC emissions from **(A)** treated pine **(B)** treated spruce samples.

painting more effectively reduces overall emission intensity than glazing. This is likely due to the opaque, pore-blocking nature of paint, which acts as a more complete barrier to VOC diffusion compared to the semi-transparent glazed coating. The comparison between painted pine and aspen showed a moderate Pearson correlation (0.607) and a high cosine similarity (0.86), indicating that painted pine mimics the structural pattern of VOC emissions seen in aspen but still differs in the concentration of specific compounds. In other words, painting shifts pine's emission behavior toward that of a naturally low-emitting wood, without fully matching it. Interestingly, glazed pine and aspen also shared a high cosine similarity (0.949) but a low Pearson correlation (0.461), again suggesting a similar emission profile structure but substantial differences in emission intensities.

Overall, the results show that 95% of the total emissions observed from all tested samples originated from untreated pine (47%), stained pine (38%), and oak (9%). In contrast, the lower emissions observed from untreated and stained spruce, painted pine, and aspen suggest that these materials may be more suitable for indoor environments with limited ventilation or where indoor air quality is a high priority.

4 Conclusion

This study provides a comprehensive analysis of total emissions (TVOC + TVVOC) from nine different untreated and treated commercial wood panels commonly used in indoor environments. Using a passive test chamber method combined with PTR-TOF-MS, the research identifies key emitted compounds and evaluates the impact of various surface treatments on VOC emission profiles. Unlike traditional gas chromatography (GC), PTR-TOF-MS enables simultaneous measurement of both very volatile and volatile compounds, offering a more detailed and time-efficient analysis.

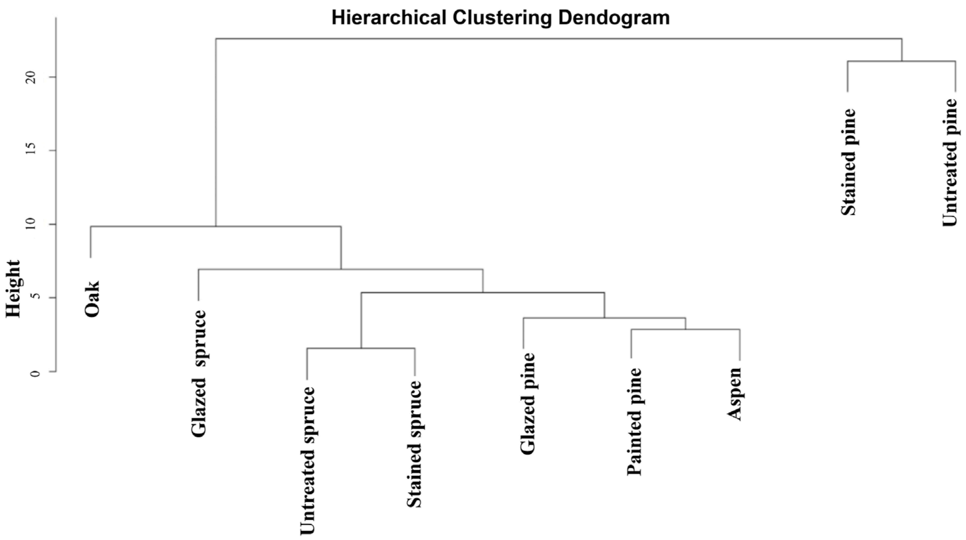

FIGURE 12
Hierarchical clustering dendrogram of the total emissions from wood samples.

Furthermore, unlike previous studies that primarily focused on untreated wood, this research examines final, marketed products, providing a more practical perspective on VOC emissions from indoor wall materials.

The findings reveal that emission patterns, intensity, and profiles are strongly influenced by both the type of untreated wood and the applied surface treatment. Untreated pine and oak exhibited the highest total emissions, while untreated spruce had the lowest. For example, the total emissions (TVOC + TVVOC) from untreated pine exceeded 37,000 µg/m^3—nearly 13 times those from untreated spruce—and were dominated by terpenes and hydrocarbons. Oak emissions were characterized by oxygenated hydrocarbons ($C_nH_mO_t$), including formaldehyde and ketene, while spruce predominantly emitted VVOCs (65%) after 7 days.

Surface treatments significantly altered both emission intensity and chemical composition. Glazing, staining, and painting decreased terpene emissions in pine by approximately 71%, 52%, and 89%, respectively, while reducing aromatic compound emissions by 94%, 86%, and 97%. Staining transformed pine's emission profile by reducing VOC emissions by 74% while increasing VVOC emissions by 63%, introducing a more chemically diverse VVOC spectrum. These changes were mainly due to alterations in the emission intensity of terpenes, aromatic compounds, and aldehydes. Glazing reduced pine's total emissions by 81% but increased emissions from spruce by 65%, highlighting the differing sensitivities of these wood types to treatment. These findings confirm that while wood type determines baseline emission behavior, surface treatments can either suppress or exacerbate VOC release depending on their chemical interactions. Treatments such as painting and glazing can transform high-emission woods like untreated pine into materials with emission profiles resembling lower-emitting species such as aspen—at least in terms of the types of compounds emitted. However, some treatments caused unintended changes in health-relevant compounds. For instance, glazing unexpectedly increased methanol emissions in spruce, while staining led to elevated aldehyde emissions in pine. These results underscore the need for treatment-specific evaluations and demonstrate that reduced total emissions do not necessarily correspond to lower health risks.

The comparison of measured emission intensity of main compounds with available Lowest Concentration of Interest (LCI) thresholds highlights that untreated pine and oak exceeded LCI values for monoterpenes, acetate, and formaldehyde, while aspen surpassed the formaldehyde limit. After finishing, painted and glazed pine fell well below the monoterpene limit, while stained pine met the threshold ($Ci/LCI \approx 1.0$). No exceedances were observed for treated spruce. Thus, surface treatments are generally effective in mitigating terpene-related health concerns; however, freshly stained pine may still warrant additional ventilation in low-airflow interiors to keep early-stage emissions comfortably within safe limits. These findings emphasize the importance of informed material selection, appropriate surface treatment choice, and adequate ventilation during and after installation to support healthy indoor air quality. This is particularly critical in Nordic regions, where energy-efficient construction often limits ventilation, increasing the likelihood of prolonged exposure to indoor pollutants. Based on both emission intensity and chemical composition, treated spruce or aspen is preferable over untreated pine or oak for use in low-ventilation environments.

Some limitations must be acknowledged. The passive test chamber method used simulates a sealed, non-ventilated environment, which may not fully reflect real-world indoor conditions. As a result, VOC concentrations measured in this study may be higher than those obtained using standardized emission chambers (ISO 16000-9, 2024). Additionally, while PTR-TOF-MS offers high sensitivity and real-time detection, it has technical limitations. At VOC concentrations exceeding 11,000 ppb, detector saturation may occur, potentially affecting accuracy. Ionization efficiency is biased toward compounds with high proton affinity and may be influenced by humidity. In complex emission matrices, PTR-TOF-MS is also susceptible to matrix effects that can impact quantification reliability. Moreover, the instrument was calibrated using acetone only, which may bias absolute concentrations for compounds such as terpenes or aromatics. However, mass drift was minimal, and the uniform application of the calibration factor across all samples ensures that any residual bias is canceled out in inter-panel comparisons.

Future research should investigate long-term VOC emissions under dynamic indoor conditions that incorporate ventilation, humidity changes, and temperature variation. Additionally, exploring a broader range of low-emission surface treatments—particularly water-based or bio-based alternatives—could contribute to more sustainable material use in healthier indoor environments.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

SG: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. JF: Investigation, Methodology, Resources, Validation, Writing – review and editing. SR: Investigation, Methodology, Resources, Validation, Writing – review and editing. SN: Data curation, Formal Analysis, Software, Writing – review and editing. TS: Project administration, Supervision, Writing – review and editing, Funding acquisition. HK: Project administration, Supervision, Writing – review and editing, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2025.1591669/full#supplementary-material

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