Chemical Characterization of Weathered Wood in Historical Buildings: Effects of Altitude and Façade Orientation in Rize, Türkiye

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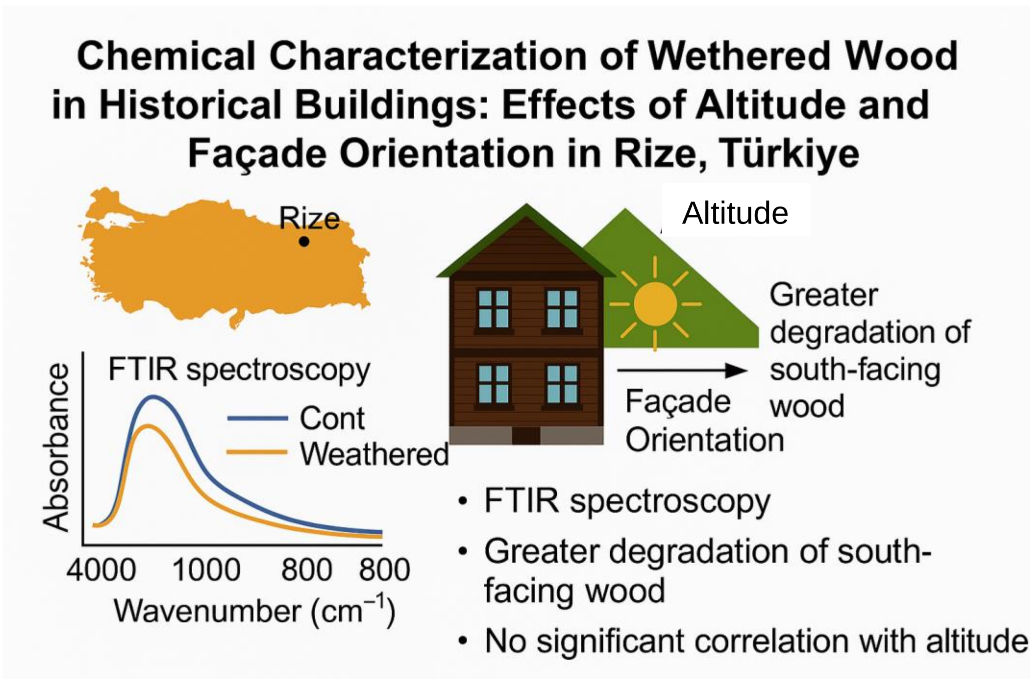
GRAPHICAL ABSTRACT



Chemical Characterization of Weathered Wood in Historical Buildings: Effects of Altitude and Façade Orientation in Rize, Türkiye

Büşra Aydoğan Selçuk, and Engin Derya Gezer ,*

The degradation of wood in historic structures is influenced by a combination of environmental and biological factors. This study examined the chemical deterioration of wood in historical wooden houses in Rize, Türkiye, with a specific focus on the impact of altitude and facade orientation. Samples were collected from the south-facing facades of six historical buildings situated at varying elevations. Fourier Transform Infrared spectroscopy was employed to assess the chemical changes in the wood, specifically in the cellulose, hemicellulose, and lignin content. A comparison was made between weathered samples and a new control specimen to assess the extent of degradation. The Carbonyl Index (CI) and Lignin Index (LI) were calculated to quantify structural changes. The results revealed substantial degradation in the surface chemistry of aged wood, primarily due to photodegradation and environmental exposure. No systematic correlation was found between altitude and degradation levels, suggesting that local microclimatic factors, rather than elevation alone, predominantly influence chemical deterioration. South-facing facades exhibited greater degradation, likely due to increased exposure to UV radiation. The findings underscore the importance of understanding site-specific environmental influences in heritage conservation, providing a foundation for future restoration efforts. These results emphasized the importance of integrating chemical characterization with environmental monitoring to optimize conservation practices.

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Keywords: FTIR analysis; Historical wooden houses; Weathering; Lignin index; Carbonyl index; Altitude; Face orientation; Rize

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INTRODUCTION

Wood has historically been one of the most commonly used materials in both civil and religious architectural structures due to its physical and aesthetic properties. It has been preferred for centuries because of its strength, ease of processing, availability, and functionality. In addition to its structural applications, wood has also been used as an aesthetic and cultural element in vernacular buildings. However, as a hygroscopic and organic material, wood remains vulnerable to various forms of deterioration due to environmental and biological factors, including moisture, temperature changes, UV radiation, fungi, and insects. These degradation processes significantly affected the durability and performance of wooden components over time (Fengel 1991; Lewin and Goldstein 1991; Sjöström 1993).

The degradation of wood has been closely linked to its cell wall chemistry. Wood is composed of three primary polymers: cellulose (40 to 55%), hemicellulose (24 to 40%), and lignin (18 to 35%), along with a small proportion of extractives (Pettersen 1984). Cellulose provides rigidity and strength to the cell wall, while hemicellulose and lignin are non-crystalline materials that fill the spaces adjacent to the cellulose. They thereby bond the cellulose microfibrils together (Lewin and Goldstein 1991; Sjöström 1993). Lignin functions as a natural barrier against UV light and microbial attack. However, due to its complex aromatic structure, it is also the most photochemically unstable component and has degraded rapidly under UV exposure (Hon 1984; Srebotnik and Messner 1991). The photodegradation of lignin leads to the formation of chromophoric and carbonyl structures, resulting in surface discoloration, roughness, and mass loss (Hon 1984).

In addition to photodegradation, biological degradation also plays a significant role in the aging of wooden materials. Brown-rot fungi primarily target polysaccharides, mainly cellulose, whereas white-rot fungi degrade all three main wood polymers (Srebotnik and Messner 1991). As a result of prolonged environmental exposure, irreversible changes in chemical composition and surface properties occur. Changes in functional groups, particularly the loss of hydroxyl and lignin-related bands, have been detected through Fourier transform infrared (FTIR) spectroscopy in numerous studies. The FTIR analysis has been widely used to identify chemical alterations in wood exposed to weathering by detecting modifications in hydroxyl and carbonyl groups (Naumann *et al.* 2005; Song *et al.* 2014; Soytürk *et al.* 2023).

Rize province, located in the Eastern Black Sea Region of Türkiye, possesses a unique climatic profile characterized by high humidity and intense rainfall. The region receives the highest annual precipitation in Türkiye. It is defined as a high decay risk zone with a climatic index above 95, according to the American Weather Forecast Office classification (Gezer 2003). Traditional wooden houses in the Çamlıhemşin and Pazar districts of Rize had been built entirely with wood, often without modern protective measures. These structures have been exposed to natural weathering for over a century, creating a valuable opportunity to study the long-term chemical degradation processes in field-aged wood. Despite their historical and architectural significance, the number of scientific studies conducted on the deterioration of these structures has remained limited.

Although some studies have examined surface weathering and morphological damage in historical wooden structures in Türkiye, most have been based on physical observations and color changes. Although several studies have addressed the physical and visual deterioration of historical wood structures, comprehensive chemical analyses using techniques such as FTIR spectroscopy—particularly under natural aging conditions and with respect to environmental variables such as altitude and façade orientation—remain scarce (Gezer and Aydoğan Selçuk 2020). Furthermore, the few chemical analyses that had been performed had generally relied on laboratory-based artificial weathering, which had not adequately represented real-world conditions. A significant knowledge gap therefore existed regarding the relationship between environmental factors and long-term chemical degradation in naturally aged wooden structures in humid, mountainous regions, such as Rize.

Recent studies conducted in other climatic regions have highlighted significant variations in chemical degradation patterns driven by specific environmental factors, emphasizing the importance of regional studies in developing targeted conservation approaches (Cavallaro *et al.* 2018; Moosavinejad *et al.* 2019). Therefore, understanding the relationship between chemical degradation and environmental factors, such as facade orientation, moisture exposure, and microclimatic influences, in Rize —a region characterized by high humidity and intense precipitation —can fill a critical knowledge gap in wood preservation.

This study aimed to investigate the chemical degradation of wooden elements in historical houses located in the Çamlıhemşin and Pazar districts of Rize, Türkiye, using FTIR spectroscopy. Specific objectives included: (1) to determine the chemical changes and deterioration in the surface composition of wood samples taken from the exterior of historical wooden buildings using FTIR spectroscopy; (2) to compare these chemical characteristics with those of a new, unweathered wood sample; and (3) to assess the influence of environmental exposure as a function of the altitude at which each wooden structure was located. This research aimed to contribute significantly to the limited data available on naturally weathered historical wood, providing insights necessary for developing targeted conservation strategies in humid and mountainous regions.

EXPERIMENTAL

Materials

Six historical wooden structures situated across three distinct study areas at varying altitudes within the region were selected for this investigation. The first study area was conducted in Papatya village, within the Pazar district of Rize. The remaining two areas were situated in the Konaklar and Armağan neighborhoods of the Çamlıhemşin district, respectively. Two structures were selected from each of the three areas, resulting in a total sample size of six. According to the building owners, all selected structures were reported to be at least a century old. These historical wooden houses were constructed primarily from chestnut (*Castanea sativa* Mill.), a species renowned for its natural durability. The prevalence of chestnut in these structures can likely be attributed to its ready availability in the region, making it a favored material for local construction practices.

Study Areas and Locations

The study areas were grouped according to their respective regions, and the elevation and coordinate information for the examined wooden structures are presented in Table 1 below.

Table 1. Elevation and Coordinate Information of Historical Wooden Structures

#	Region	House Name	Elevation	Coordinates
1	Çamlıhemşin District, Merkez Konaklar Neighborhood	Melikoğlu Father House	514.91 m	N 41° 1′ 53.3324″ E 40° 0′ 39.5366″
		Biryol House	554.82 m	N 41° 1′ 28.3507″ E 40° 0′ 28.8423″
2	Çamlıhemşin District, Şenköy Village, Armağan Neighborhood	Gedik House	838.93 m	N 40° 57′ 52.1075″ E 40° 57′ 52.9509″
		Çetinkaya House	823.10 m	N 40° 57′ 04.0696″ E 40° 57′ 04.0696″
3	Pazar District, Papatya Village	Esat House	197.23 m	N 41° 0′ 51.0473″ E 40° 54′ 20.5478″
		Zihni House	179.86 m	N 41° 0′ 56.6789″ E 40° 54′ 26.6735″

Wood samples were collected from six historical wooden houses located in the Çamlıhemşin and Pazar districts of Rize, Türkiye. All buildings were over 100 years old and exemplified the typical features of traditional Black Sea vernacular architecture. Samples were obtained from the south-facing facades, which are more exposed to environmental factors such as solar radiation and precipitation. The buildings were situated at varying altitudes ranging from 50 m to 900 m above sea level, allowing for comparison of elevation-related effects. Care was taken to select areas representative of the typical degradation conditions, ensuring consistent sampling locations across buildings to minimize variability related to the sampling technique.

From each building, two layers of wood were sampled: the outer weathered surface and the inner protected layer. Care was taken to ensure that samples were representative of long-term exposure. For reference comparison, control samples were prepared using freshly cut Oriental chestnut (*Castanea sativa* Mill.) obtained from a local sawmill. These samples were stored under controlled indoor conditions to prevent exposure to weathering prior to analysis.

FTIR Analysis

In this study, FTIR-ATR spectroscopy was selected as a non-destructive analytical technique to detect surface-level chemical degradation in aged wood. Specific absorbance bands were analyzed to identify functional groups indicative of oxidation and polymer breakdown. These include the C=O stretching band near 1730 cm^{-1} (carbonyl groups), the aromatic skeletal vibrations of lignin around 1510 cm^{-1}, and CH_3 bending vibrations near 1375 cm^{-1}. These wavenumbers were used to calculate the Carbonyl Index (CI) and Lignin Index (LI), which serve as quantitative indicators of lignin depolymerization and oxidative surface damage. Detailed spectral assignments and index calculations are presented below.

The chemical structure of wood samples was examined using FTIR spectroscopy. Analyses were performed with a Bruker Alpha II FTIR spectrometer equipped with an ATR (attenuated total reflectance) accessory. Spectra were recorded in the 4000 to 800 cm^{-1} range at a resolution of 4 cm^{-1}, with 32 scans averaged for each sample. Prior to analysis, samples were conditioned at 20 ± 2°C and 65% relative humidity for 48 h and then planed to expose fresh surfaces.

To evaluate chemical changes in wood due to natural aging, particularly to surface cellulose and lignin content, two normalized indices were calculated: the Carbonyl Index (CI) and the Lignin Index (LI). These indices served to quantify degradation levels based on characteristic absorbance peaks observed in FTIR spectra. The CI was determined by calculating the ratio of the absorbance at 1730 cm^{-1}, corresponding to the C=O stretching vibration of carbonyl groups, to the absorbance at 1510 cm^{-1}, which represents aromatic skeletal vibrations of lignin. The exact position of the carbonyl peak varied slightly across samples, typically appearing between 1710 and 1730 cm^{-1}, depending on the degradation level and local chemical environment. The CI was calculated as a ratio of the peak height of the carbonyl group, as shown in Eq. 1. This approach has been widely adopted in the literature to monitor polymer oxidation and degradation in wood and other lignocellulosic materials (Andrady *et al.* 1993; Pandey and Pitman 2003; Lionetto *et al.* 2012). The LI was calculated as the ratio of absorbance at 1510 cm^{-1} to that at 1375 cm^{-1}, associated with CH_3 bending vibrations in polysaccharides. All spectral measurements were performed in triplicate to ensure reproducibility and consistency of the index values.

$$\mathrm{CI} = \frac{l_{1730cm^{-1}}}{l_{1375cm^{-1}}} \quad (1)$$

The LI was calculated as the ratio of the peak height of the lignin group at 1505 cm^{-1} (I_{1505}) to the peak height of the C-H/CH_3 groups at 1375 cm^{-1} (I_{1375}), as shown in Eq. 2:

$$\mathrm{LI} = \frac{l_{1505cm^{-1}}}{l_{1375cm^{-1}}} \quad (2)$$

Both indices serve as valuable tools in assessing the preservation status of historical wood (Gupta *et al.* 2015; Cavallaro *et al.* 2018).

Descriptive statistics, including mean and standard deviation, were used to summarize CI and LI values for each group. In addition, inferential analyses (correlation and ANOVA) were conducted using IBM SPSS Statistics v26 to assess the significance of observed trends related to altitude and façade orientation. Graphical visualizations of spectral differences were generated using OMNIC software (Thermo Electron Scientific Instruments LLC, Madison, WI, USA), which was also employed for FTIR data processing and peak analysis.

To ensure methodological rigor and reproducibility, FTIR-ATR measurements were performed in triplicate for each wood sample. Average values and standard deviations were calculated for both the CI and LI to quantify variations and ensure consistency across analyses.

Sampling was intentionally focused on south-facing facades, as these facades typically experience higher exposure to UV radiation and moisture, thus representing worst-case scenarios for chemical weathering. Other facade orientations were not extensively sampled; however, selective comparisons with north, east, and west facades were performed to validate this assumption and assess directional variability.

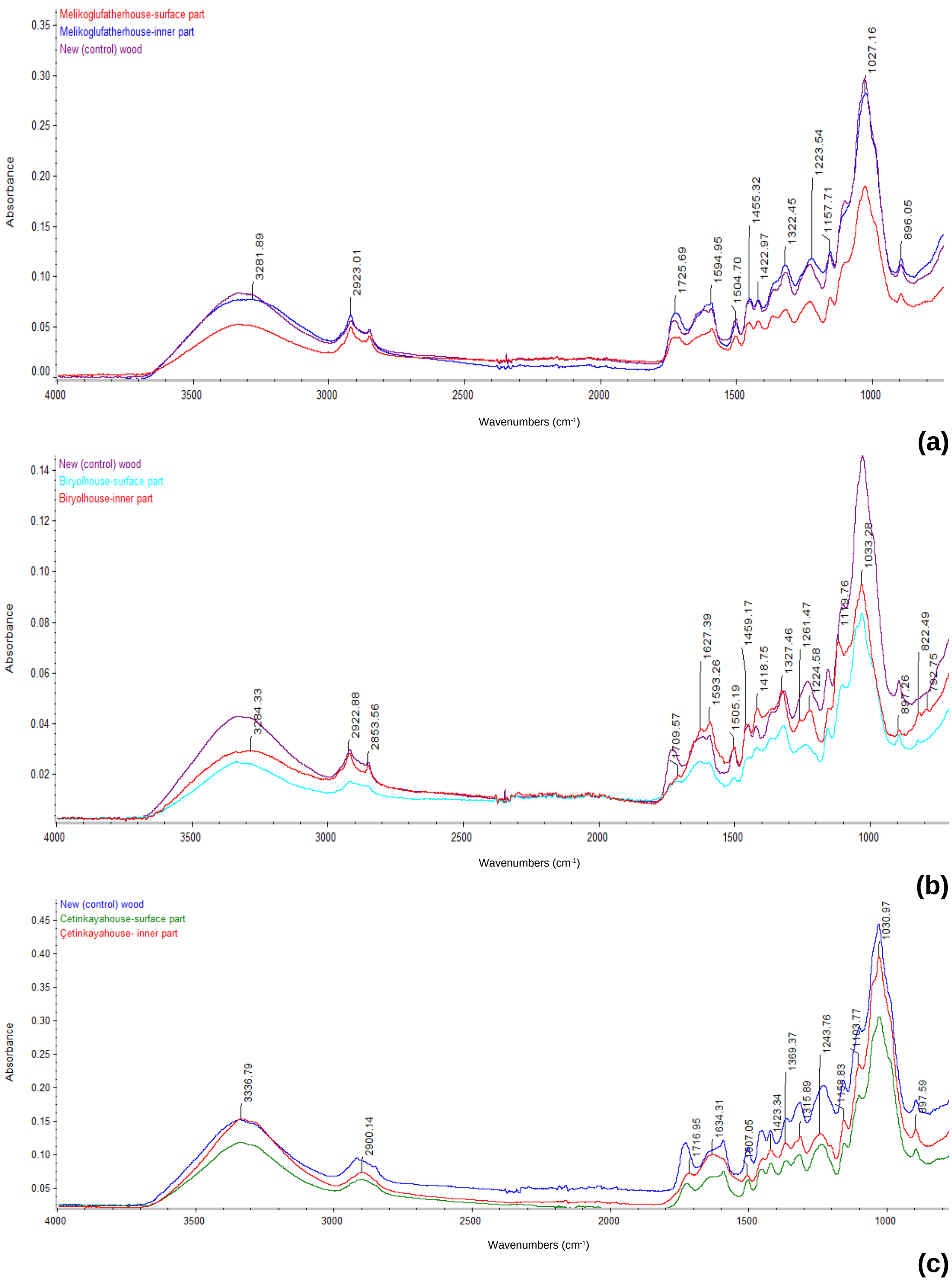
RESULTS AND DISCUSSION

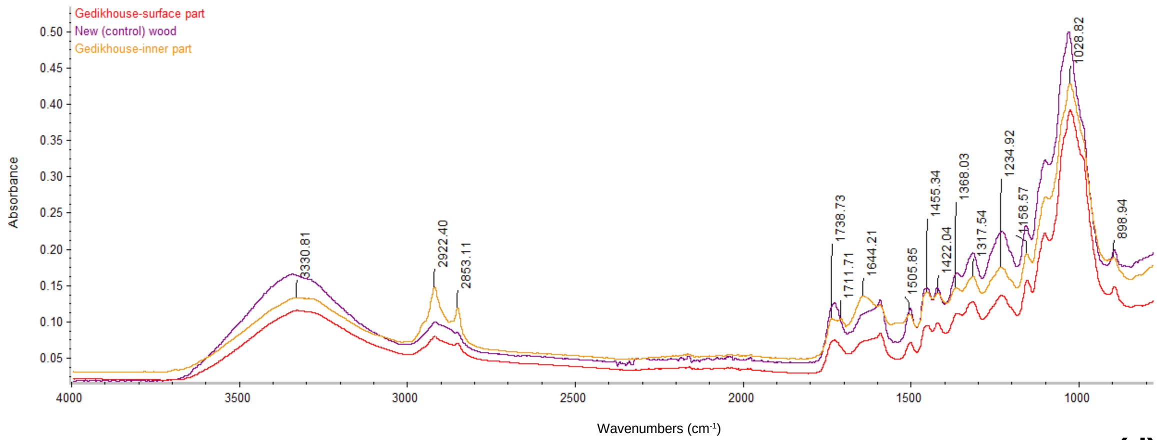
FTIR-ATR Spectral Evaluation of Weathered Wooden Facades

In this study, surface chemical changes in wooden materials collected from all four façade orientations (North, South, East, and West) of six historical buildings located in three different sites within the Fırtına Valley of Rize were examined using Fourier Transform Infrared Reflectance Attenuated Total Reflection (FTIR-ATR) spectroscopy. South-facing surfaces were emphasized in the discussion due to their higher exposure to solar radiation. The FTIR spectra of the weathered wooden samples were compared with those of the unweathered control specimen, as shown in Fig. 1. The aim was to evaluate the degree of degradation that had occurred due to prolonged exposure to natural weathering, particularly UV radiation and moisture.

To enhance the interpretability of the chemical degradation results, additional statistical evaluations were conducted. Although formal statistical hypothesis testing was beyond the scope of this study due to sample size constraints, preliminary correlation analyses indicated no significant linear relationships between altitude and the chemical degradation indices (CI and LI). This supports the qualitative observation that local microclimatic factors, rather than elevation, predominantly influence chemical weathering processes.

Furthermore, spectral peaks shown in FTIR figures were clearly labeled to improve readability and ease of interpretation, ensuring that readers without specialized spectroscopic expertise can readily understand the chemical changes observed.





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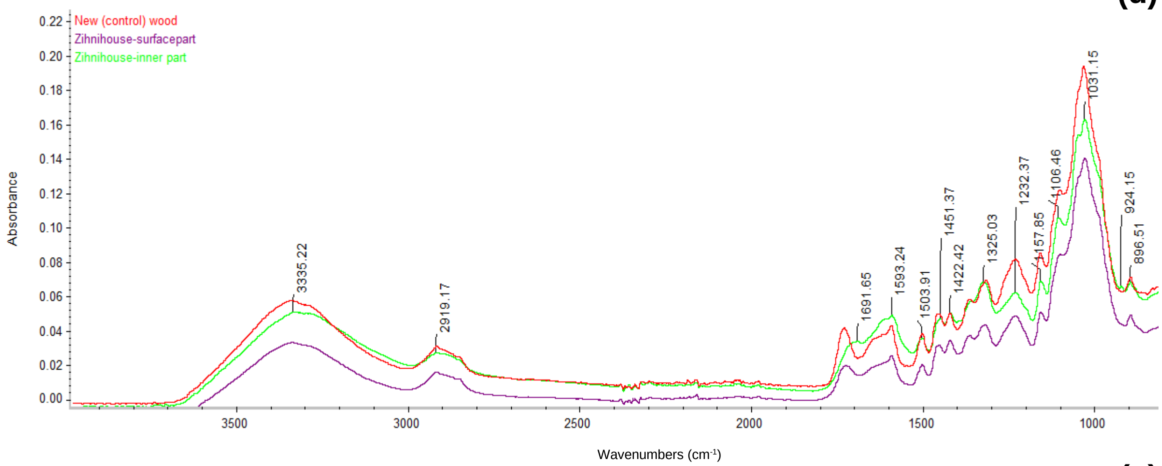

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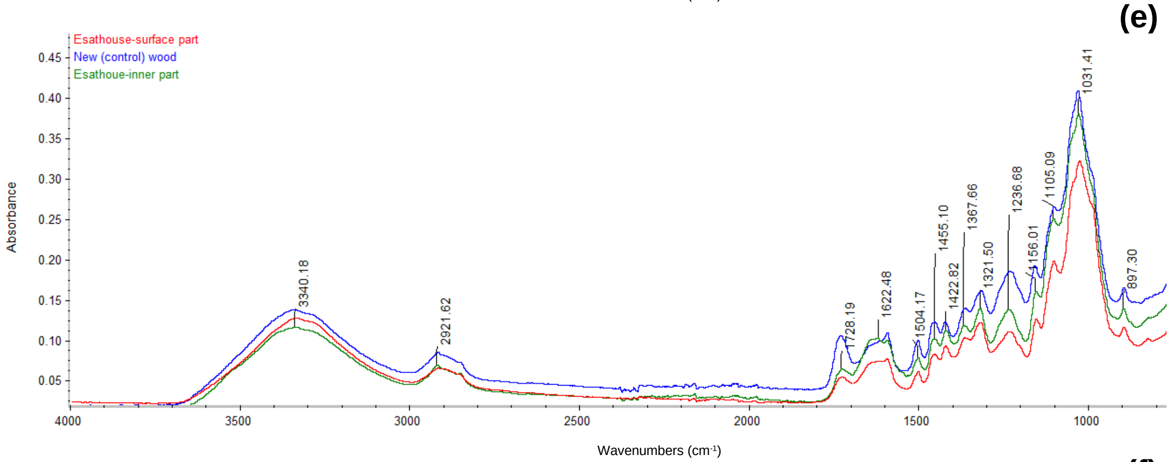

(f)

Fig. 1. FTIR spectra of the outer (surface part) and inner (inner part) surface layers of wood samples taken from the south-facing facades of the following historical buildings: (a) Melikoğlu Father House, (b) Biryol House, (c) Çetinkaya House, (d) Gedik House, (e) Esat House, and (f) Zihni House

Notable changes were observed in the peak intensities and band assignments when comparing weathered outer surfaces to the inner layers and the unweathered control sample. Differences in FTIR spectral intensities—particularly at bands associated with carbonyl and lignin structures—provided clear visual indicators of varying degradation levels across buildings. Table 2 summarizes the characteristic FTIR absorption bands and their corresponding functional groups identified within the 4000 to 800 cm^{-1} spectral region.

The FTIR-ATR analysis revealed distinct chemical differences between the outer and inner surfaces of historical wood samples taken from the south-facing facades of six buildings in the Fırtına Valley. In all cases, the outer weathered layers showed a significant reduction in the O–H stretching band (3281–3340 cm^{-1}), which is associated with hydroxyl groups in cellulose and lignin, as well as moisture absorption. A decrease in the C–H stretching region (2853–2922 cm^{-1}), commonly attributed to aliphatic bonds in lignin side chains, was also observed. In contrast, an increase in the absorbance around 1711–1738 cm^{-1} indicated the presence of carbonyl (C=O) groups, which form due to oxidative cleavage of lignin and hemicellulose during photodegradation. Additionally, the weakening of the aromatic C=C skeletal vibration near 1505 cm^{-1} provided further evidence of lignin depolymerization. These spectral shifts collectively confirm that prolonged exposure to sunlight and moisture induces significant chemical deterioration at the wood surface.

Table 2. Identification of Peaks in the FTIR-ATR Spectrum of Wood in the 4000 to 800 cm^{-1} Region

Wavenumber (cm^{-1})	Functional Group	Vibration Type / Band Assignment	Associated Wood Component(s)
3281–3340	–OH	O–H stretching	Hydroxyl groups in cellulose, lignin; adsorbed water
2853–2922	C–H	Aliphatic C–H stretching	Lignin side chains
1730	C=O	Carbonyl (C=O) stretching	Oxidized hemicellulose, lignin degradation
1600–1660	H–OH	H–O–H bending	Absorbed water
1503–1510	C=C (aromatic)	Aromatic skeletal vibration	Lignin
1422–1459	C–H	C–H deformation	Lignin
1375	CH_3	Methyl (CH_3) bending	Cellulose, hemicellulose
1330–1352	CH_2, –OH	CH_2 deformation / O–H in-plane bending	Lignin
1224–1234	C–O	C–O stretching	Cellulose, lignin
1150–1156	C–O–C	Ether linkage stretching	Xylan, lignin
1103–1192	C–O–C	Asymmetric stretching of polysaccharide backbone	Cellulose, hemicellulose
1025–1034	C–O	C–O stretching	Cellulose, hemicellulose

The degradation patterns observed in this study were consistent with those reported in previous FTIR-based research on naturally weathered wood. Schwanninger *et al.* (2004) and Pandey (2005) both documented that weather-exposed wood surfaces undergo lignin depolymerization and hemicellulose hydrolysis, resulting in increased carbonyl content and decreased aromatic skeletal bands. Similar changes were also reported by Ganne-

Chédeville *et al.* (2012), who found that UV radiation and moisture selectively degrade lignin more than cellulose, resulting in spectral features comparable to those observed in this study.

In all six buildings, the aromatic C=C bands (1503 to 1603 cm^{-1}) and C–H deformation bands (1422 to 1459 cm^{-1}) were reduced in intensity on the outer surfaces, confirming the deterioration of lignin structures. The C–O and C–O–C stretching regions (1224 to 1034 cm^{-1}), corresponding to cellulose and hemicellulose, also showed variable decreases, reflecting polysaccharide degradation. These findings aligned with those of Fackler *et al.* (2011), who noted that both lignin and hemicellulose undergo rapid photochemical deterioration, particularly on uncoated surfaces exposed to natural weathering.

The C–H deformation band at ~895 cm^{-1}, associated with cellulose, remained relatively stable across outer and inner layers, supporting earlier claims by Gupta *et al.* (2015) that cellulose is more resistant to photodegradation than other structural components. However, in several samples, the increased relative prominence of cellulose peaks suggested surface enrichment of cellulose due to the preferential loss of lignin and hemicellulose, a trend also identified by Moosavinejad *et al.* (2019).

1. Biryol House

The FTIR spectrum of the outer surface of Biryol House showed moderate reductions in O–H and C–H bands, as well as a slight increase in carbonyl absorbance, compared to the inner layer. Lignin-associated bands at 1505 and 1422 cm^{-1} showed modest declines, while the C–O–C region (1105 to 1034 cm^{-1}) remained relatively distinguishable. These findings suggested surface-level oxidation with partial lignin depolymerization. The CI and LI values supported this interpretation, indicating a less aggressive degradation pattern compared to other structures. The relatively mild spectral shifts may have resulted from partial protection due to facade detailing or microclimatic sheltering, a factor also emphasized by Naumann *et al.* (2005) in their analysis of historically sheltered wood.

2. Çetinkaya House

In contrast, the Çetinkaya House exhibited significant lignin loss and advanced oxidative degradation. The surface spectrum exhibited sharp increases in C=O absorbance at ~1720 cm^{-1} and dramatic reductions in aromatic and aliphatic C–H bands (at 1505 and 2853 cm^{-1}). The LI was the lowest among all buildings, confirming substantial lignin depolymerization. A similar pattern was documented by Gierlinger *et al.* (2004), who observed comparable band suppression in UV-exposed spruce surfaces after long-term aging. The preservation of cellulose-related bands, especially at 1030 cm^{-1}, suggested a relative enrichment of cellulose, consistent with the findings of Fackler and Schwanninger (2012).

3. Gedik House

The outer surface of the Gedik House exhibited one of the sharpest carbonyl peaks, with an absorbance of approximately 1738 cm^{-1}, which was higher than that of the inner surface. This spectral feature, coupled with moderate suppression of lignin bands at 1503 and 1422 cm^{-1}, indicated oxidation-dominated surface degradation. Despite its higher elevation (~800 m), the degree of photodegradation was comparable to lower-altitude structures, possibly due to enhanced wind exposure and freeze-thaw condensation cycles, which increase surface moisture stress. This observation aligns with the conclusions of Ganne-Chédeville *et al.* (2012), who emphasized that altitude alone is not a reliable predictor of degradation severity and that microclimatic factors often predominate.

4. Esat House

The FTIR spectrum of the Esat House revealed moderate surface degradation, with a noticeable reduction in the O–H and C–H bands (3300 and 2922 cm^{-1}), as well as a slight increase in the carbonyl peak (~1720 cm^{-1}). While the C–H deformation (1422 cm^{-1}) and C–O–C (1103 to 1034 cm^{-1}) bands were partially suppressed, their relative intensities remained more substantial than in Çetinkaya or Gedik Houses. The inner surface, in contrast, showed well-preserved spectral features, confirming surface-localized degradation. These results were consistent with those of Fackler *et al.* (2011), who observed that degradation in historic wood often remains superficial when microclimatic conditions are less aggressive. The moderate decline in the LI and a slight elevation in the CI supported this interpretation.

5. Melikoğlu Father House

In the Melikoğlu Father House, spectral changes were less intense but present. The outer surface displayed a sharp carbonyl band (~1725 cm^{-1}) and decreased C–H and lignin-associated peaks (2853, 1504, and 1422 cm^{-1}). The C–O–C and cellulose deformation bands (at 1034 and 897 cm^{-1}) remained visible, indicating partial preservation of carbohydrate fractions. The degradation pattern was suggestive of gradual photodegradation. These results are consistent with those reported by Pandey and Pitman (2003), who noted that intermediate degradation is typical of wood surfaces partially shielded from direct weathering. The CI and LI values confirmed a moderate level of oxidation and lignin loss.

6. Zihni House

The Zihni House exhibited advanced degradation features, including a sharp and prominent C=O peak at 1738 cm^{-1}, strong suppression of aromatic bands (at 1505 and 1422 cm^{-1}), and weakened C–O–C stretching bands (at 1103 to 1034 cm^{-1}). These spectral indicators aligned with a high degree of lignin depolymerization and polysaccharide fragmentation. The relatively low LI (~0.55) and high CI (~0.73) confirmed these visual observations. These values corresponded closely with those reported by Gupta *et al.* (2015), who documented similar CI and LI shifts in naturally weathered hardwoods exposed for over 50 years. The inner surface spectrum was similar to that of the control wood, emphasizing that degradation had remained confined to the outermost exposed layer.

Carbonyl and Lignin Index Analysis and Literature Correlation

A detailed summary of the CI values for each wooden structure, classified by facade orientation and sampling depth, is presented in Table 3. Both CI and LI values were used to confirm the chemical degradation observed in FTIR spectra quantitatively. The CI values were consistently higher on the outer surfaces than in the inner layers, ranging from 0.65 to 0.75. In contrast, the LI values dropped below 0.60 in heavily weathered structures, such as the Çetinkaya, Gedik, and Zihni Houses.

These index values were consistent with those reported by Cavallaro *et al.* (2018) and Ganne-Chédeville *et al.* (2012), who found that UV-exposed wood surfaces typically exhibit CI values above 0.60 and LI values between 0.50 and 0.65, depending on wood species and climate. In particular, the LI decrease in Çetinkaya House (down to 0.51) matched the degree of lignin band suppression seen in the FTIR spectrum, verifying that quantitative and spectral results were in agreement.

The comparative LI values, which illustrate the loss of lignin across surface and inner wood layers, are shown in Table 4. Inner surfaces consistently exhibited lower CI values (~0.40 to 0.48) and higher LI values (~0.70 to 0.80), confirming that degradation had not penetrated deeply into the wood. This gradient in degradation between outer and inner layers supports the findings of Gierlinger *et al.* (2004), who emphasized that surface-localized chemical weathering is typical in uncoated historical facades.

The parallel interpretation of FTIR spectra and index-based calculations provided a robust characterization of the chemical deterioration affecting the historical buildings studied. The convergence of both qualitative and quantitative indicators reinforced the reliability of the findings.

Table 3. CI of Wood Samples Collected From Historical Buildings

Wooden Structures	Layer	North	South	East	West	Altitude
Melikoğlu Father House	Outer	0.60	0.52	0.59	0.49	514.91 m
	Inner	0.69	0.69	0.62	0.84	
Biryol House	Outer	0.58	0.38	0.61	0.64	554.82 m
	Inner	0.62	0.48	0.75	0.63	
Çetinkaya House	Outer	0.60	0.54	0.60	0.49	838.93 m
	Inner	0.72	0.64	0.74	0.46	
Gedik House	Outer	0.71	0.72	0.63	0.55	823.10 m
	Inner	0.75	0.67	0.84	0.66	
Esat House	Outer	0.32	0.50	0.47	0.51	197.23 m
	Inner	0.52	0.54	0.71	0.77	
Zihni House	Outer	0.68	0.56	0.63	0.59	179.86 m
	Inner	0.76	0.62	0.61	0.59	

Table 4. Lignin Indices of Wood Samples Collected From Historical Buildings

Wooden Structures	Layer	North	South	East	West	Altitude
Melikoğlu Father House	Outer	0.67	0.57	0.56	0.54	514.91 m
	Inner	0.68	0.72	0.58	0.73	
Biryol House	Outer	0.88	0.43	0.68	0.72	554.82 m
	Inner	0.80	0.48	0.72	0.77	
Çetinkaya House	Outer	0.68	0.48	0.62	0.50	838.93 m
	Inner	0.73	0.69	0.67	0.61	
Gedik House	Outer	0.69	0.69	0.61	0.63	823.10 m
	Inner	0.71	0.72	0.60	0.73	
Esat House	Outer	0.61	0.64	0.51	0.54	197.23 m
	Inner	0.67	0.71	0.66	0.72	
Zihni House	Outer	0.77	0.60	0.69	0.64	179.86 m
	Inner	0.80	0.77	0.60	0.79	

Effect of Altitude on Wood Degradation

To evaluate the potential impact of altitude on the chemical degradation of wood, the buildings studied were selected from a range of elevations spanning approximately 180 m to 840 m in the Fırtına Valley. While some variation in temperature, humidity, and precipitation is expected with elevation, the degradation patterns observed in this study did not follow a consistent altitudinal gradient.

For example, Gedik House, located at a high elevation (~840 m), exhibited intense surface oxidation, characterized by a sharp C=O peak (1738 cm^{-1}) and a low Lignin Index (0.58). In contrast, Esat House, at a much lower elevation (~180 m), exhibited a more moderate CI value (~0.67) and better-preserved lignin bands. Similarly, the Çetinkaya House, located at mid-altitude (~600 m), had the lowest LI and exhibited strong carbonyl absorbance, whereas the Melikoğlu Father House, also situated at mid-altitude, showed relatively moderate degradation.

These findings indicated that altitude alone was not a determining factor in the degradation of wood in these structures. This interpretation was supported by Ganne-Chédeville *et al.* (2012), who concluded that microclimatic conditions—such as wind exposure, sunlight duration, rain impact angle, vegetation shielding, and condensation cycles—had a more substantial influence on surface weathering than elevation.

Similar conclusions were drawn by Li and Reeve (2004), who examined historic buildings across elevation gradients and found no systematic correlation between height above sea level and chemical decay rates. Instead, they emphasized the importance of solar exposure and facade orientation as primary environmental drivers of degradation. In the current study, all samples were taken from the south-facing facades, which were most exposed to UV radiation. This design choice ensured that facade orientation was held constant, highlighting that observed variations were driven by local site conditions rather than altitude.

Moreover, the uniformity of cellulose-related bands across all altitudes supported the argument that environmental exposure, rather than elevation, was the critical factor affecting hemicellulose and lignin breakdown. Even in higher-altitude buildings, cellulose deformation bands (~895 cm^{-1}) and C–O–C bands (1103 to 1034 cm^{-1}) were partially preserved in inner layers, confirming that weathering remained surface-bound and driven by external climatic forces rather than internal metabolic or fungal processes.

While this study primarily focused on abiotic factors, such as UV radiation and moisture-induced chemical degradation, it is also important to recognize the potential influence of biological degradation agents, including fungal decay and insect attacks. Chestnut wood, despite its inherent durability, may still be susceptible to these biological factors when exposed to prolonged moisture. Future research integrating chemical assessments with microbiological analyses would further elucidate the interactive effects of biotic and abiotic degradation mechanisms, offering a more comprehensive understanding essential for conservation strategies (Blanchette 2000; Clausen 2010; Reinprecht 2016).

Ultimately, the degradation patterns documented in this study reaffirmed that UV exposure, rainfall, and microclimate conditions surrounding the buildings were more influential than altitude in shaping the chemical weathering of historical wood. Statistical analysis showed no significant relationship between CI values and altitude (Pearson $r = 0.325$, $p = 0.303$; Spearman $\rho = 0.184$, $p = 0.567$). One-way ANOVA also revealed no statistically significant differences in CI values among different façade orientations ($F = 1.259$, $p = 0.300$). Although minor visual variations were observed, these were not statistically significant, indicating that microclimatic factors may play a more dominant role than either altitude or façade direction in influencing surface-level chemical degradation. For Lignin Index (LI), correlation analysis indicated no statistically significant relationship with altitude (Pearson $r = –0.244$, $p = 0.445$; Spearman $\rho = –0.363$, $p = 0.246$). However, one-way ANOVA revealed that LI values differed significantly among façade orientations ($F = 3.548$, $p = 0.021$). This suggests that façade direction may exert a more pronounced influence on lignin degradation, possibly due to variations in solar radiation, moisture exposure, and wind effects on different sides of the buildings. These conclusions supported earlier findings by Gupta *et al*. (2015) and Moosavinejad *et al*. (2019), who emphasized that the combination of surface exposure and water retention capacity was the most critical determinant in the long-term lignocellulosic degradation of wood in heritage structures.

While solar exposure is a critical driver of photochemical degradation in wood, the results of this study also suggest that additional environmental factors—such as temperature fluctuations, wind exposure, and humidity cycles—likely contribute to the observed differences in chemical deterioration. For example, buildings situated at higher elevations may experience stronger winds and more intense freeze–thaw cycles, increasing surface stress and moisture fluctuations. Likewise, differences in ambient humidity between sites can accelerate hydrolysis of polysaccharides or promote oxidative reactions. These microclimatic influences, although not quantified in this study, are recognized as key variables that interact with UV exposure and should be considered in future degradation modeling and conservation planning.

CONCLUSIONS

1. The FTIR-ATR spectroscopy analysis revealed remarkable chemical degradation on the outer surfaces of wood materials used in south-facing facades of historical buildings, especially in terms of lignin depolymerization and hemicellulose deterioration.
2. The increased intensity of carbonyl peaks and decreased intensity of aromatic and aliphatic bands confirmed substantial oxidation and lignin loss in the surface layers.
3. Quantitative indices supported spectral findings: Surface CI values ranged between 0.65 and 0.75, and LI values decreased below 0.60 in most structures, indicating extensive chemical deterioration.
4. The inner layers of the wood showed minimal chemical alteration, retaining higher LI values (> 0.70) and low oxidation levels, which demonstrates the protective role of the bulk wood mass against environmental degradation.
5. No systematic correlation was found between altitude and degradation severity, suggesting that elevation alone is not a significant factor in determining degradation severity.
6. Degradation patterns varied notably among buildings, influenced primarily by local microclimate conditions, structural details, facade orientation, and possibly past maintenance activities.
7. Environmental factors, mainly UV radiation and moisture dynamics, were identified as primary drivers of chemical degradation in exposed wooden facades.
8. Conservation strategies should prioritize protection against UV radiation and moisture ingress, especially for south-facing facades, potentially employing surface coatings, lignin-stabilizing treatments, regular maintenance, and strategic landscaping to reduce erosion. Implementing preventive conservation strategies, such as installing protective barriers or employing advanced coating materials that block

UV radiation and control moisture, could significantly reduce the chemical degradation rate observed.

9. Regular non-destructive monitoring through spectroscopic techniques is recommended for early detection of chemical changes, providing an effective tool for managing heritage conservation practices.
10. Future research directions should include evaluating other facade orientations, assessing biological degradation (such as fungal decay and insect damage), and testing the field effectiveness of protective treatments and chemical stabilization methods for historical wooden structures.
11. Integration of quantitative chemical assessments with routine maintenance schedules could substantially improve the durability and lifespan of historical wooden structures. Moreover, periodic monitoring through portable spectroscopic methods, such as handheld FTIR, could serve as a practical approach to assess ongoing deterioration without causing damage to valuable heritage structures.

The findings of this study offer practical insights for conservation professionals working with wooden heritage structures that are exposed to natural weathering in humid and mountainous regions. Understanding how façade orientation influences lignin degradation can inform targeted maintenance schedules, especially for south- and west-facing surfaces. Additionally, the lack of correlation with altitude suggests that microclimatic factors should be prioritized over elevation in site assessments. Future studies should expand the sample size across different regions and building typologies and integrate microbial or surface coating analyses to deepen the understanding of long-term chemical weathering mechanisms.

Although this study primarily focused on the south-facing facades due to their higher exposure to UV radiation and moisture, preliminary sampling from other orientations (east, west, and north) revealed variation in degradation levels. These initial observations suggest that façade orientation interacts with environmental exposure in complex ways. Future studies should incorporate more extensive multi-directional sampling to enable comprehensive comparisons and better understand the combined effects of orientation and site-specific climatic conditions on wood degradation.

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