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ORIGINAL ARTICLE

Site variability in chemical compositions and color parameters of black locust (*Robinia Pseudoacacia* L.) wood

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Abstract

Robinia pseudoacacia L. has a valuable wood due to its natural durability and resistance to decay and external environments. This durability is attributed to its high content of extractives and the amount of tyloses in earlywood vessels. Given the widespread occurrence of black locust across Hungary, the wood chemical components may differ depending on site growth conditions. This research investigated the chemical extractives and color parameters of wood from *Robinia pseudoacacia* L. from different counties and growth conditions in Hungary. The relationship between chemical extractives and color based on the CIElab system was also analysed. The results indicated that both counties and growth conditions showed significant variations in chemical extractives and color parameters. The counties of Vas and Győr-Moson-Sopron exhibited the highest total contents of extractives, polyphenol, antioxidant capacity and intense lightness. Compatible outcomes were recorded under poor growth condition mixed species. Lightness was significantly associated with extractives from methanol-water and total phenol contents with lightness. While the extractive from the cyclohexane-ethanol solvent system was linked with all color parameters. Subsequent research will investigate the impact of extractives on wood durability under different locations and growth conditions.

1 Introduction

The black locust (*Robinia pseudoacacia* L.), a rapidly growing deciduous tree native to North America, has been extensively cultivated throughout Europe and other regions (Han et al. 2000; Nicolescu et al. 2018; Nicolescu et al. 2020). In Central and Northern Europe, it is regarded as a significant alternative to native species because of its notable drought tolerance and adaptability to climate change (Ciuvăţ et al. 2022; Brischke et al. 2024). It can regenerate through both root sprouts and seeds (Rédei et al. 2012).

In Hungary, *Robinia pseudoacacia* L. trees are planted both alone and mixed with other species like Populus and poplar, thriving in both good-quality and poor-quality soils. They are widely distributed across Hungary, from the northeast to the south and southwest of the country (Rédei et al. 2008, 2011; 2017). They occupy approximately 24.42% (458.296 ha) of the forested area (Csaba 2023), providing 25% of the annual wood requirements (Rédei 1999; Rédei and Meilby 2000, 2009).

It is well known that wood is a renewable material, composed of cellulose, hemicellulose, lignin, and small amounts of extractives (Shmulsky and Jones 2011). The presence of extractives and phenolic compounds, especially in mature heartwood, enhances black locust's popularity for outdoor and decorative uses due to its increased durability, resistance to decay, and distinctive colouration (Latorraca et al. 2011; Rédei et al. 2019). A previous study examined the variability in extractives and ash content in *Robinia pseudoacacia* L., from the bottom to the top of a single tree, from pith to bark, and across different species. Variability in chemical composition occurs due to factors such as the age

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of the trees, the difference between sapwood and heartwood, and site conditions during growth, including both micro and macro environmental factors. Tree growth conditions are influenced by a complex interaction of climatic, edaphic, and biological factors. Key environmental determinants, such as temperature, photoperiod, light intensity, moisture levels, soil nutrient status, and gravity, play crucial roles in shaping the formation, structure, and chemical composition of wood (Adamopoulos et al. 2005; Stringer and Olson 1987; Németh et al. 2018; Traoré et al. 2023).

Several studies have explored the relationship between wood color parameters and extractives content in *Robinia pseudoacacia* L., with particular attention to the effect of thermal treatments on lightness and redness and yellowness (Fan et al. 2010; Wei et al. 2017; Preklet et al. 2023). However, data regarding the chemical extractives and the color of wood *Robinia pseudoacacia* L., and their relationship in Hungary, remains limited. This study aimed to examine site variability in chemical composition, including the ash content, total extractives content, total polyphenol content, and antioxidant capacity of *Robinia pseudoacacia* L. wood sourced from five Hungarian counties and under three growth conditions. Furthermore, wood color, such as lightness, redness, and yellowness, was assessed to evaluate their relationships with chemical extractives. Due to climate change, *Robinia pseudoacacia* may be an alternative species in Hungary (Rédei et al. 2018); therefore, the result of this study is crucial for identifying optimal sites for planting Robinia trees to promote high resistance to decay and produce durable wood.

2 Materials and methods

2.1 Wood material

As displayed in Table 1, *Robinia pseudoacacia* L. wood was collected from eleven locations, representing five Hungarian counties. Namely, Bács-Kiskun and Baranya (Middle Hungary), Szabolcs-Szatmár-Bereg (Northeastern Hungary), Vas (western Hungary) and Győr-Moson-Sopron (Northwestern Hungary) as shown in Fig. 1. The site growth condition of the sample trees was categorized as: (1) GGC-good growth conditions, which had rusty brown forest sandy soil about 60–100 cm deep, high fertility, good structure, balanced nutrient levels, adequate drainage, and a pH level between 6 and 7, (2) PGC-poor growth conditions, which had rusty brown forest loamy soil with stagnant water about 40–100 cm deep, low fertility, poor structure, compacted, waterlogged, and high salinity and (3) MPGC-poor growth conditions mixed species (Tóth et al. 2007; Várallyay 2015). Table 1 further presents the number of discs, tree ages, diameter at breast height (DBH) and the geographic coordinates of the sample sites within each county. To eliminate potential genetic variation, no hybrid varieties were used in this study.

The climatic variables of the study area, encompassing the average annual and maximum temperatures as well as total annual precipitation, were calculated from 1982 to 2023 and are summarised in Table 2 (National Aeronautics and Space Administration (NASA) 2025).

2.2 Sampling

Samples were prepared from 22 logs. Two discs (4 cm in thickness) were extracted from each log at breast height (130–140 cm). The first discs had been used to examine the chemical compositions. While the second discs were used to evaluate the color parameters. Using a drill, wood particles

Table 1 County, sites within county under investigation (Younis et al. 2025)

County	Sites within the County	Number of logs/sites	Tree ages	DBH (cm)	Growth condition	Coordinates
Bács-Kiskun (sourced from KAFEG company)	Balotaszállás	2	35	24.5	GGC	68,6546°N, 10,9105°E
	Kunfehértó	3	38	17	PGC	67,4622°N, 11,4344°E
Szabolcs-Szatmár-Bereg	Ófehértó 33	2	38	26	GGC	87,7527°N, 29,1922°E
	Ófehértó 31	2	40	22	PGC	87,8676°N, 29,0636° E
	Pap	2	33	26	GGC	88,1955°N, 32,1529°E
	Baktalórántháza	2	40	27	PGC	87,5568°N, 29,6031°E
Vas	Telekes	3	47	27	MPGC	47,5547°N, 17,9632°E
Baranya	Ibafa	1	37	22	GGC	46,0918°N, 17,5459° E
	Ibafa	1	30	20	PGC	
Győr-Moson-Sopron (sourced from TAEG company	Iván	2	40	18	PGC	47,44633°N, 16,91224°E
	Iván	2	38	27	GGC	

GGC good growth condition, *PGC* poor growth condition, *MPGC* mixed stand on poor growth condition, *DBH* diameter at breast height

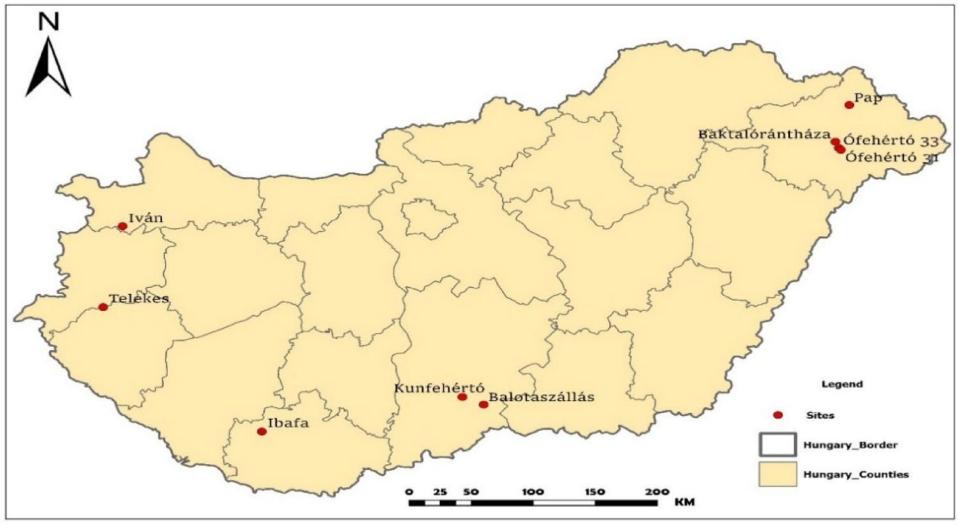

Fig. 1 Study area map with specific locations for wood sample collection within the County by name (Younis et al. 2025)

Table 2 Historical climate data, annual temperature and precipitation, for the study area over a 40-year period from 1982 to 2023

County	Avg Temp (°C)	Max Temp (°C)	Sum annual Preci (mm)	Ave Preci
Bács-Kiskun	11.5	37.7	585.1	48.8
Szabolcs-Szatmár-Bereg	10.6	35.8	593.5	49.5
Vas	11.0	36.2	634.6	52.9
Baranya	11.4	37.1	739.2	61.6
Győr-Moson-Sopron	10.7	36.1	642.0	53.5

Ave average, *Temp* temperature, *Preci* precipitation

Fig. 2 Wood particles extracted by drill from the disc of *Robinia pseudoacacia* L. before grinding

were obtained from heartwood (both juvenile and mature wood) (Adamopoulos and Voulgaridis 2002), as shown in Fig. 2.

2.3 Determination of ash content

The moisture content of wood particles was first assessed using a moisture balance device, with three replicate samples, each weighing 2–3 g. Subsequently, 0.2–0.4 g of wood particles were heated in an oven at 550 °C for a duration of 1–2 h. After that, the ash content was calculated and given as a percentage of the original samples according to EN 14775:2010.

2.4 Determination of extractives content

The wood particles were ground using a coffee blender. Then, approximately 0.2 to 0.25 g of powder (0.2–0.63 sieve fraction) was placed into test tubes, designated as groups A and B. After that, 20 ml of a methanol-water (1:1, v/v) solvent was added to group A, while 20 ml of a cyclohexane-ethanol (1:1, v/v) solvent was added to group B. The test tubes containing the powder and solutions were covered with aluminium foil to reduce solvent evaporation during ultrasonic treatment in a bath for 60 min. Following sonication, solid residues were removed from the extract using filter paper. Six millilitres of the filtered extract were transferred to the pre-weighed aluminium vessel. The containers with the extracts were kept at laboratory temperature for 24 h to ensure the complete evaporation of the solvents. Finally, the dried extracts were weighed to determine the final mass of the dry extract. The total extractives content is expressed as a percentage of the initial samples. Three replicates were conducted for each sample to obtain methanol-water soluble extract content (MWE) and cyclohexane-ethanol soluble extract content (CYE). The sum of these contents gave the total extractive content (TEC) (Fodor and Hofmann 2024).

2.5 Determination of total polyphenol content (TPC)

TPC was determined using the Folin-Ciocâltău technique (Singleton and Rossi 1965). A solution of 0.5 ml of methanol-water was mixed with 2.5 ml of 10x diluted Folin-Ciocâltău reagent. Then, after 1 min, 2.0 ml of 0.7 M sodium carbonate (Na_2CO_3) solution was added to the mixture. The reaction mixture was heated in a water bath at 50 °C for 5 min, then cooled in cold water. The absorbance was measured via a spectrophotometer at 765 nm. The gallic acid standard has been used to determine the polyphenol content, expressed in mg of gallic acid equivalents per gram of dry wood (GAE/g/dw).

2.6 Determination of antioxidant capacity using ferric reducing antioxidant power method (FRAP)

From the wood extract used for TPC analysis, 50 µl was combined with 1.5 ml of FRAP reagent (25 ml of 300 mM acetate buffer pH 3.6, 2.5 ml of 20 mM $FeCl_3$ solution, and 2.5 ml of 10 mM TPTZ solution). Afterwards, the solution was shaken for 5 min, during which a blue color developed. The absorbance was determined at 593 nm. The antioxidant capacity was calculated from absorbance, using a calibration curve constructed from a standard series of ascorbic acids (0.19, 0.40, 0.60, 0.80, and 1.0 mmol/liter).

2.7 Assessment of color parameters

The present study measured the wood color on the transverse surface, even though tangential surfaces are more common in wood products and are more relevant for visual and commercial uses. A choice justified as providing a reliable, composite measurement of the bulk material (Hirata et al. 2020). Wood discs were precisely sanded with 180 and 80-grit sandpaper and cleansed with compressed air (Fig. 3). Specimens 2 cm in thickness and 4 cm in width, spanning from bark to bark, were prepared. The specimens were conditioned in a climate chamber at a temperature of 20 °C and a relative humidity of 65%; they reached an approximately 12% moisture content. The CIELAB parameters were determined using the D65 illuminant. Thirty replicates were measured from the wood samples for each location within the county, with a test window of 5 mm in diameter. The CIELab color system measures wood color using three values: lightness (L*), which goes from 0 for black to 100 for white; redness (a*), which shows how red or green the color is, with + 100 for red and − 100 for green; and yellowness (b*), which shows how yellow or blue the color is, with + 100 for yellow and − 100 for blue (Tolvaj and Varga 2012; Baar et al. 2014).

Fig. 3 Color measurement specimens

2.8 Data analysis

The data was analysed using R statistical software packages (V4.3.2 (2023-10-31 ucrt)). Normality and homogeneity were checked using the Shapiro-Wilk and Levene tests, respectively. In the scenario, the ANOVA showed significant variations, and Tukey's HSD test was applied to investigate the differences between the groups. Pearson's correlation coefficient was applied to investigate the relationships between wood color parameters with extractives and total polyphenol contents.

3 Results and discussion

3.1 Chemical composition differences across counties and growth conditions

Table 3 displays the average and standard deviation of ash content, extractive content, TPC, and FRAP, along with their variability across counties. Vas County recorded the highest values for all variables studied, except that the ash (0.29%) and CYE (1.57%) contents were the lowest. In contrast, Baranya County showed the lowest values for MWE (5.04%), TEC (7.37%), TPC (15.1 GAE/g dw), and FRAP (6.03 mg AA/g dw). The differences in chemical compositions, indicated by small letters above the averages (Tukey HSD test), show whether there are significant differences, with uniform letters indicating no significant differences ($P \leq 0.05$) and different letters indicating significant differences. The ash content and CYE did not vary significantly across counties.

Table 3 Average and standard deviation (SD) of chemical composition of wood *Robinia Pseudoacacia* L. for five Hungarian counties

County	Ash (%)	MWE (%)	CYE (%)	TEC (%)	TPC GAE/g/dw)	FRAP (mg AA/g dw)
Győr Moson Sopron	0.47±0.10^{a}	9.35±0.20^{bc}	1.60±0.26^{a}	10.9±0.33^{b}	28.4±2.58 ^{bc}	14.7±0.34^{bc}
Bács Kiskun	0.41±0.09^{a}	7.69±0.64^{ab}	3.42±0.72^{a}	11.1±0.45^{b}	24.4±1.28^{b}	11.1±1.73^{b}
Baranya	0.31±0.07^{a}	5.04±0.74^{a}	2.33±1.72^{a}	7.37±2.26^{a}	15.1±3.70^{a}	6.03±1.87^{a}
Szabolcs Szatmár Bereg	0.31±0.15^{a}	7.37±2.20^{ab}	2.23±0.94^{a}	9.61±1.88^{ab}	25.2±5.32^{b}	11.5±2.81^{b}
Vas	0.29±0.19^{a}	11.8±1.15^{c}	1.57±0.76^{a}	13.4±1.90^{b}	36.0±0.66^{c}	17.8±0.42^{c}
All	0.36±0.13	7.77±2.30	2.29±1.10	10.06±2.23	24.77±6.71	11.59±3.88

MWE extractives in methanol/Water, *CYE* extractives in Cyclohexane-Ethanol, *TEC* total extractives content, *TPC* total phenol content, *FRAP* Ferric Reducing Antioxidant Power

Table 4 Growth conditions- average and (SD) of chemical composition of wood *Robinia Pseudoacacia* L.

Growth condition	Ash content (%)	MWE (%)	CYE (%)	TEC (%)	TPC (GAE/g dw)	FRAP (mg AA/g dw)
GGCs	0.35±0.17^{a}	7.52±1.64^{a}	2.53±1.16^{a}	10.1±1.47^{a}	23.7±5.15^{b}	11.6±3.13^{ab}
PGCs	0.38±0.07^{a}	7.21±2.35^{a}	2.20±1.11^{a}	9.41±2.48^{a}	23.6±6.89^{b}	10.6±3.86^{b}
MPGCs	0.29±0.19^{a}	11.8±1.15^{b}	1.57±0.75^{a}	13.4±1.90^{a}	36±0.65^{a}	17.8±0.42^{a}

MWE extractives in methanol/Water, *CYE* extractives in Cyclohexane-Ethanol, *TEC* total extractives content, *TPC* total phenol content, *FRAP* Ferric Reducing Antioxidant Power, *GGCs* good growth conditions, *PGCs* poor growth conditions, *MPGCs* poor growth conditions (mixed species)

Table 5 Average and standard deviation (SD) of color parameters of wood *Robinia Pseudoacacia* L. for five Hungarian counties

County	L*	a*	b*
Győr Moson Sopron	59.4±4.78^{bc}	2.64±1.38^{b}	30.2±3.07^{c}
Bács Kiskun	56.8±7.73^{ab}	3.30±1.63^{ab}	28.0±4.83^{b}
Baranya	56.2±3.14^{a}	3.44±1.46^{a}	27.6±2.77^{ab}
Szabolcs Szatmár Bereg	57.6±5.45^{ab}	4.25±1.39^{c}	26.3±2.29^{a}
Vas	62.0±3.15^{c}	2.83±1.32^{ab}	27.8±2.68^{ab}

*L** lightness, *a** redness, *b** yellowness

Table 6 Growth conditions-average and standard deviation of color parameters of wood *Robinia Pseudoacacia* L.

Growth conditions	L*	a*	b*
GGCs	58.92±5.89^{c}	3.39±1.52^{ab}	27.05±3.75^{b}
PGCs	56.15±4.90^{b}	3.76±1.61^{b}	28.32±3.06^{a}
MPGCs	62±3.15^{a}	2.83±1.32^{a}	27.84±2.68^{ab}

*L** lightness, *a** redness, *b** yellowness, *GGCs* good growth conditions, *PGCs* poor growth conditions, *MPGCs* poor growth conditions mixed species

Table 4 presents the chemical extractives and their variations across different growth conditions. The ash content ranged from 0.29% (in MPGC) to 0.38% (in PGC), while CYE and TEC ranged from 1.57% (in MPGC) to 2.53% (in GGC), and from 9.41% (in PGC) to 13.4% (in MPGC), respectively. No significant differences in ash content, CYE, and TEC were observed among the growth conditions, although other variables showed variations.

Although the average ash content values across all counties ranged from 0.29% to 0.47%, they did not vary significantly. Similar trends were observed for growth conditions, even though the soil qualities differed. This result is not consistent with findings that the ash content of Robinia wood samples from Greece, Bulgaria, and Hungary is associated with soil growth conditions (Passialis et al. 2008). Compared to our finding, a higher range (0.32%–0.61%) for ash content was reported in Bulgaria (Panayotov et al. 2015).

Regarding extractives content, previous studies have focused on juvenile and mature wood. They found that hot water extractives in heartwood are higher than in sapwood and increase from the bottom to the top of the tree (Adamopoulos et al., 2005). Within the heartwood, the mature heartwood exhibits higher extractive and phenol content than juvenile wood (Dünisch et al. 2010; Sergent et al. 2014; Vek et al. 2020; Hofmann et al. 2024).

3.2 Color parameters differences across counties and growth conditions

Table 5 presents the means and standard deviations (SD) of the wood color parameters across the surveyed counties. Significant inter-county variation in L*, a*, and b* was confirmed (Table 4). The L* values ranged from 56.2 (Baranya) to 62.0 (Vas). The a* values spanned from a minimum of 2.64 (Győr-Moson-Sopron) to a maximum of 4.25 (Szabolcs-Szatmár-Bereg). Similarly, b* values varied, ranging from 26.3 (Szabolcs-Szatmár-Bereg) to 30.2 (Győr-Moson-Sopron).

With an average value of 62, MPGCs had the highest L* among the growth conditions. Conversely, PGCs displayed the lowest value, averaging 56.15. While the a* and b* were intense in PGCs, with an average value of 3.76 and 28.32, respectively (Table 6). The analysis of variance (ANOVA) test showed significant variability ($p<0.05$) in color parameters between growth conditions. The Tukey test (HSD) indicates that L* significantly varied among all growth

Table 7 Pearson's correlation between color parameters and extractives content of wood *R. pseudoacacia* L.

Parameters	MWE	CYE	TEC	TPC	L*	a*	b*
MWE	1	−0.40 ns	0.85***	0.88***	0.55**	−0.35 ns	0.05 ns
CYE	−0.40 ns	1	−0.01 ns	−0.32 ns	−0.52*	0.47*	−0.59**
TEC	0.85***	0.01 ns	1	0.82***	0.36 ns	−0.10 ns	−0.22 ns
TPC	0.88***	−0.32 ns	0.82***	1	0.48*	−0.08 ns	−0.07 ns
L*	0.55**	−0.52*	0.36 ns	0.48*	1	−0.23 ns	0.26 ns
a*	−0.35 ns	0.47*	−0.10 ns	−0.08 ns	−0.23 ns	1	−0.74***
b*	0.05 ns	−0.59**	−0.22 ns	−0.07 ns	0.26 ns	−0.74***	1

ns not significant; p>=0.05; * $p<0.05$; ** $p<0.01$; *** $p<0.001$; *MWE* methanol-water, *CYE* cyclohexane-ethanol, *TEC* total, *TPC* total phenol content, *L** lightness, *a** redness, *b** yellowness

conditions. However, the a* differs only between PGCs and MPGCs. In line, the b* differs between PGCs and GGCs.

The researchers indicated that the variation in wood color is due to multiple factors, such as tree species, genetic resources, tree age and silvicultural management (Nishino et al. 1998; Moya and Berrocal 2010; Csordós et al. 2014). Gierlinger et al. (2004) found that genetics had a stronger effect on color than growth site for Larch heartwood. Klumpers et al. (1993) reported that Oak trees grown in soil with abundant water produced dark and reddish wood color. Campos et al. (2025) reported that tree age significantly influenced color parameters of teak wood, apart from lightness.

Compared to the earlier study, the wood color of *Robinia pseudoacacia* L. (from both fast-growing and control types) in Hungary showed higher L* (65) and a* (7) values, but a lower b* value (28) (Csordós et al. 2014). Similarly, Tolvaj et al. (2013) reported great L* and lower b*, whereas the a* value (4.18) was comparable to that observed in Szabolcs-Szatmár-Bereg County. Moreover, compared to the Austrian Robina the redness and yellowness showed higher values (13.3 and 37.4, respectively) than our result (Meints et al. 2017).

3.3 Pearson's correlation between wood color parameters with extractives and phenol contents

Despite the limitation of this study is that color parameters were assessed on the transverse section, Table 7 summarises the correlation coefficients between wood color parameters and the chemical extractives of *Robinia pseudoacacia* L. The result revealed that MWE and TPC correlated significantly and positively with L* ($r=0.55$, $p<0.01$ and $r=0.48$, $p<0.05$, respectively). In contrast, CYE showed a negative relationship with L* ($r = -0.52$, $p<0.05$) and b* ($r = -0.59$, $p=0.01$), and a positive correlation with a* ($r=0.47$, $p<0.05$); notably, TEC was not significantly correlated with color. The positive correlation between L* and TPC in the current study contradicts the general principle that darker heartwood is linked to higher phenol content (Moya 2010; Pâques et al. 2013), a deviation likely attributable to the methodological choice of assessing color on the transverse section instead of the tangential surface. Several studies investigated the correlation between color parameters (L*, a* and b*) and chemical extractives in sapwood and heartwood, including Teak (Lukmandaru et al. 2011; Feng et al. 2025), *Acacia mangium* and *Vochysia guatemalensis* (Moya et al. 2012), African Padauk and Jatoba (Barr et al. 2014).

4 Conclusion

The chemical composition of *Robinia pseudoacacia* L. wood, involving ash content, extractives, and total polyphenol content, was assessed across different locations and growth conditions in Hungary. In addition, wood color parameters were determined and correlated with extractive yield and phenol contents.

Across Hungary, Vas and Győr Moson Sopron counties revealed the highest extractives and polyphenol content, plus antioxidant capacity. In terms of growth condition, the MPGCs yield the greatest chemical extractives and the lowest ash content compared to GGC and PGC. Both the methanol-water extract and the total phenol content were linked with lightness. However, cyclohexane-ethanol is associated with all color parameters. While the total extractives content was not correlated with any.

This study was limited by the fact that the wood material from Vas County was collected from one location characterised by poor growth conditions and mixed species. Future research should address this aspect while also examining durability across countries and varying growing environments. These results are significant for wood applications and for forest management in Hungary, and in our opinion, it can provide a good basis for examining wood materials from other regions.

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Data availability The data of this study are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

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