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EFFECT OF ENVIRONMENTAL FACTORS ON ANATOMICAL, CHEMICAL, PHYSICAL AND MECHANICAL PROPERTIES OF HUNGARIAN BLACK LOCUST (*ROBINIA PSEUDOACACIA* L.) WOOD AS FUNCTION OF GEOGRAPHICAL LOCATIONS

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Sopron

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Dissertation for doctoral (PhD) degree

Written by:
Fath Alrhman Awad Ahmed Younis

Made in the framework of the József Cziráki Doctoral School, University of Sopron
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Abbreviations

DBH	Diameter at breast height.
GGC	Good growth conditions.
PGC	Poor growth conditions.
MPGC	Poor growth conditions mixed species.
FL	Fiber length
FW	Fiber width.
FWT	Fiber wall thickness.
LD	Lumen diameter
RW	Ring width.
TEC	Total extractives content.
MWE	Extractives from methanol-water.
CYE	Extractives from cyclohexane-ethanol.
TPC	Total polyphenol content.
ADD	Air dry density or density at 12% moisture content.
BD	Basic density.
RSH	Radial shrinkage.
TSH	Tangential shrinkage.
LSH	Longitudinal shrinkage.
VSH	Volumetric shrinkage.
RSW	Radial swelling.
TSW	Tangential swelling.
LSW	Longitudinal swelling.
VSW	Volumetric swelling.
MOE	Modulus of elasticity.
MOR	Modulus of rupture.
CS	Compressive strength parallel to the grain.

Abstract

Black locust is a widely cultivated plantation species with a substantial global distribution. In Hungary, it covers approximately 24.42% of the total forested area, and its wood is valued for its high durability and resistance to environmental factors. Given its broad distribution across the country, the properties of *Robinia pseudoacacia* L. wood may vary considerably among different regions. Therefore, this research was aimed to investigate the physical, anatomical, chemical and mechanical properties of wood *Robinia pseudoacacia* L. across Hungary under different growth conditions. Also, the study analysed the relationship between temperature and precipitation with ring width and fiber length. As well as the relationship between chemical extractives with color parameters. A total of twenty-two logs were collected from five counties namely, Bács Kiskun, Szabolcs Szatmár Bereg, Vas, Baranya and Győr Moson Sopron. the differences in wood properties were investigated using R software programme.

Statistical analysis indicated significant differences in Robinia wood properties across Hungary and growth conditions. Across all counties, wood fiber length ranged from 1.04 to 1.11 mm, while ring width ranged from 1.25 to 3.68 mm. With greatest fiber properties produced in Szabolcs-Szatmár-Bereg and Vas counties and besides the GGC. Chemically, Vas County recorded the highest values for methanol water extractives at 11.8%, total extractives at 13.4%, total polyphenol content at 36.0 mg GAE/g dw, and antioxidant capacity at 17.8 mg AA/g dw. In contrast, Baranya County showed the lowest levels of chemical extractives and the lowest lightness values.

The mean values were 0.80±0.07 g/cm^3 for air-dry density and 0.71±0.06 g/cm^3 for basic density. Bács Kiskun and PGC–poor growth conditions recorded the highest values while the lowest values found in Baranya County and the MPGC–poor growth conditions mixed species. Mechanically, Bács Kiskun recorded the highest modulus of elasticity, while Győr Moson Sopron documented the highest modulus of rupture and compressive strength. Correlation analysis revealed a significant positive relationship between lightness with methanol water extractives as well as with total phenol content. In contrast, lightness was negatively correlated with cyclohexane ethanol extractives.

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.

A környezeti tényezők hatása a magyar fehérakác (*Robinia pseudoacacia* L.) anatómiai, kémiai, fizikai és mechanikai tulajdonságaira, a földrajzi elhelyezkedés függvényében

Absztrakt HU

A fehér akác világszerte széles körben termesztett ültetvényfaj, jelentős globális elterjedéssel. Magyarországon az összes erdőterület mintegy 24,42%-át borítja, és a faanyagát nagy tartóssága és környezeti tényezőkkel szembeni ellenálló képessége miatt különösen nagyra értékelik. Mivel az akác hazánk teljes területén megtalálható, feltételeztem, hogy a *Robinia pseudoacacia* L. faanyag tulajdonságai térségenként jelentősen eltérhetnek.

Ezért kutatásomban azt a célt tűztem ki, hogy megvizsgáljam a Robinia pseudoacacia L. fa fizikai, anatómiai, kémiai és mechanikai tulajdonságait az ország különböző régióiban, eltérő növekedési feltételei között. Elemeztem továbbá a hőmérséklet és a csapadék kapcsolatát az évgyűrűszélességgel és a rosthosszal, valamint az extraktanyagok és a színparaméterek közötti összefüggéseket is.

Ehhez összesen huszonkét rönköt gyűjtöttem be öt különböző vármegyéből: Bács-Kiskun, Szabolcs-Szatmár-Bereg, Vas, Baranya és Győr-Moson-Sopron területéről. A faanyag-tulajdonságok közötti különbségeket R szoftverrel elemeztem.

A statisztikai vizsgálatok szignifikáns különbségeket igazoltak az akác faanyag-tulajdonságaiban az egyes régiók és növekedési feltételek között. A mintákban a farosthossz 1,04–1,11 mm, az évgyűrűszélesség pedig 1,25–3,68 mm közötti értékeket mutatott. A legkedvezőbb rosthosszúsági tulajdonságokat Szabolcs-Szatmár-Bereg és Vas megyében, valamint a jó növekedést mutató állományokban tapasztaltam.

A kémiai jellemzők tekintetében Vas megye mutatta a legkedvezőbb értékeket: metanol–vizes extraktum: 11,8%, – összes extraktanyag-tartalom: 13,4%, összes polifenol-tartalom: 36,0 mg GAE/g szárazanyag, antioxidáns kapacitás: 17,8 mg AA/g szárazanyag.

Ezzel szemben Baranya megyében mértem a legalacsonyabb extraktanyag-tartalmat és a legalacsonyabb világossági értékeket.

A légszáraz sűrűség átlagértékei 0,80±0,07 g/cm³, illetve az bázis sűrűség 0,71±0,06 g/cm³ voltak. A legmagasabb értékeket Bács-Kiskun megyében és kedvezőtlen növekedési feltételek között kaptam, míg a legalacsonyabbakat Baranya megyében és gyenge növekedésű, elegyes állományokban. Mechanikai szempontból Bács-Kiskun megyében volt a legmagasabb a rugalmassági modulus, míg Győr-Moson-Sopron megyei anyagokon mértem a legnagyobb hajlító- és nyomószilárdságot.

A korrelációs elemzés során szignifikáns pozitív kapcsolatot találtam a világosság és a metanol–vizes extraktumok, valamint az összes fenoltartalom között. Ezzel szemben a világosság negatív korrelációt mutatott a ciklohexán–etanol extraktumokkal.

Véleményem szerint ezek az eredmények fontosak a faanyag gyakorlati alkalmazhatósága és az erdőgazdálkodás szempontjából Magyarországon, és megfelelő alapot nyújtanak más régiókból származó faanyagok további vizsgálatához is.

1 CHAPTER ONE

LITERATURE REVIEW

1.1 Introduction

It is a well-known fact that the atmospheric concentration of greenhouse gases (GHG) continues to increase globally (Lamb et al. 2022). Consequently, this rise has resulted in a significant increase in global temperatures. Localized data demonstrates these trends in Napkor, Hungary, a region known for significant black locust cultivation. The average temperature in 2021 was 10.7 °C. This shows a 0.3 °C increase compared to the mean temperature observed over the 1985–2020 period. The broader effects of this GHG increase include decreased precipitation, frequent drought occurrences, unpredictable rainfall patterns, flooding, biodiversity declines, and changes in photoperiod (Ábri et al. 2022). Furthermore, climate change can lead to altered hydrological cycles that transfer minerals from the soil, causing their deposition elsewhere (Larchar, 1995).

The growth condition involves climatic, edaphic, and biological components. Typically, temperature, photoperiod, light intensity, moisture, soil fertility, and gravity are key factors influencing the structure of wood (Wodzicki, 2001). Generally, the variations in wood properties may be initiated by a single environmental factor, or it may result from complex interactions between two or more factors and the genetic makeup of the species (Kim et al. 2011). Changes in growth conditions can physiologically impact wood quality, depending on the tree species. This influence is often manifested through alterations to the wood anatomical structure, such as the number of vessels in 1mm^2, ray, parenchyma, fiber, and widths, and vessel characteristics (Usta et al. 2014, Zhang et al. 2020, Nazari et al. 2020). Furthermore, the influence of tree age is a critical and established factor that cannot be overlooked when assessing wood properties (Panshin and de Zeeuw, 1980, Lowe and Greene 1990, Barajas 1997, Nugroho et al. 2012, Kalbarczyk et al. 2016, Kalbarczyk and Ziemiańska, 2016, Keyimu et al. 2021). Understanding the impact of environmental components on wood formation is complex because it is necessary to assess the consequences of radial diameters, cell wall thickness, and other impact variables responsible for these outcomes (Arnold and Mauseth, 1999).

Numerous studies have investigated the influence environmental factors on wood structure (Farrar and Evert, 1997, Rigatto et al. 2004, Ross et al. 2015, You et al.

2021). Arnold and Mauseth (1999) examined the effect of light, water, and nutrient levels on wood growth in *Cereus peruvianus* and demonstrated that low nitrogen and phosphorus treatments reduced vessel width and shoot elongation, while low light reduced vessel density. Also, high moisture levels caused broader vessels and greater shoot elongation.

A considerable correlation exists between the physical and chemical properties of soil and the variation in wood quality during tree growth. While sites with optimal soil conditions often maximize wood volume production, the resulting wood quality may not be adequate for structural applications. For instance, a study of *Tectona grandis* plantations in Costa Rica found that soil properties did not influence the wood's physical characteristics (specifically gravity and volumetric shrinkage) (Moya and Perez, 2008). However, subsequent research indicated that *Tectona grandis* grown in deep, fertile soil under dry conditions produces a darker wood color compared to those grown in wet conditions (Moya and Calvo, 2012). Conversely, air temperature and rainfall have been shown to have a notable impact, affecting the annual ring width of *Robinia pseudoacacia*. Furthermore, temperature and precipitation were found to influence the radial cell growth, secondary wall thickening, and xylem cell generation in the stem of Siberian larch (*Larix sibirica*) (Antonova and Stasova, 1997).

Regional population increases have cleared large, forested areas for farming and to supply raw materials for the wood industry. Since the amount of wood produced is insufficient to satisfy the rising demand, governments and industry are looking for fast-growing species to substitute premium quality, durable wood. Only a few tree species in Europe can produce wood with the high natural durability like black locust (Grosser 2003). *Robinia pseudoacacia* L., also called yellow locust, or false Acacia, is a promising species of the Leguminosae family. Native to the Southeast United States (Ross, 2010), it ranks among the most important globally planted tree species and is third only to eucalyptus and hybrid poplar trees in terms of economic significance. *Robinia pseudoacacia* L. trees reach heights of 12 to 18 m and have breast-height diameters of 30 to 76 cm (Huntley 1990).

Robinia pseudoacacia L. is a species of considerable value and history in Hungary, having been cultivated for 300 years (Rédei 1999; Rédei and Meilby 2000; Rédei and Meilby 2009). It is extensively planted in both pure and mixed stands across diverse ecological zones (Rédei et al. 2008), currently comprising 24.42% (458,296 ha) of the total forested area (Csaba, 2023). Recognizing its economic importance, Hungary has implemented several programs, such as the INCO-COPRNICUS project, specifically aimed at resolving cultivation limitations and enhancing wood quality. These strategic efforts have successfully driven the development of superior clonal materials (Rédei et al. 2012; Rédei et al. 2013; Rédei et al. 2019; Rédei et al. 2020; Ábri et al. 2021; Keserű et al. 2021). In 2016 between 12th to 13th May the first Robina workshop was held at Sopron University. The workshop pointed the state of art of research, innovation ideas of supply and utilizations and contact with industries, forested and regional administration.

1.1.1 Hypothesis

Although several studies having investigated the characteristics of wood *Robinia pseudoacacia* L., in many European countries (Bijak and Lachowicz, 2021; Wei et al. 2017; Pollet et al. 2012; Fan et al. 2009; Molnár and Bariska, 2002), comprehensive data concerning the anatomical, physical, chemical, and mechanical properties of wood of this species, across Hungary, remains limited. Considering the wide geographical distribution of *Robinia pseudoacacia* L., trees within Hungary, we assume that:

- The internal structural of Robinia wood can be influenced by site-specific growth conditions.
- The site-related factors play a crucial role in chemical composition of Robinia wood.
- The Variability in physical and mechanical properties of Robinia wood can be attributed to differences in site and growth conditions.

1.1.2 Research Objectives

The main objective of this study is to investigate the wood characteristics of *R. pseudoacacia* L. from five Hungarian counties and among three growth conditions.

Specific objectives are:

1. To investigate the anatomical features
    - Wood fiber length, width, wall thickness and lumen diameter
    - Vessel length and width
    - Width of the annual ring.

2. To analyse the organic and inorganic composition

- Ash content (%)
- Extractives content (%)
- Total polyphenol content (mg GAE/g dw)
- Antioxidant capacity (mg AA/g dw).

3. To determine physical properties

- Wood density
- Wood shrinkage and swelling (radial, tangential and volumetric)
- Wood color parameter

4. To investigate the mechanical properties

- Modulus of rupture
- Modulus of elasticity
- Compressive strength parallel to the grain

1.2 Background

1.2.1 The origin and description of black locust

Robinia pseudoacacia L. is an invasive tree in Central Europe and is included on national blacklists and inventories of alien species across Europe (Vtková et al. 2017). The species is highly adaptable and expands rapidly (Mantovani et al. 2014). It was introduced to Europe from North America in the 17th century and Korea in the 19th century. The species arrived in Hungary between 1710 and 1720 (Lee et al. 2004, Redei et al. 2008). The first substantial black locust forests were planted on the Great Hungarian Plain at the beginning of the 18th century to stabilize the wind-blown, sandy soil. It is spreading throughout Central Europe, including Poland, Slovakia, Slovenia, Germany, Austria, and the Czech Republic (Figure 1), and in Mediterranean countries, including Italy, France, and Greece. Notable black locust tree stands exist in Bulgaria, Croatia, Ukraine, FYR Macedonia, Belgium, Bosnia, Herzegovina, Romania, and Serbia. China and Korea are the most vital *Robinia pseudoacacia* cultivators in Asia (Vítková et al. 2017, Nicolescu et al. 2020, Vítková et al. 2020)

Black locust has expanded across Central Europe (Figure 1), including Poland, Slovakia, Slovenia, Germany, Austria, and the Czech Republic, as well as Mediterranean countries such as Italy, France, and Greece. Significant populations of black locust trees are present in Bulgaria, Croatia, Ukraine, North Macedonia, Belgium, Bosnia and

Herzegovina, Romania, and Serbia. Furthermore, it is found in Asia, with China and Korea being the most significant regions (Vítková et al. 2017; Nicolescu et al. 2020; Vítková et al. 20 20).

Figure 1: Distribution of *R. pseudoacacia* L. in Central Europe (Vítková et al. 2017).

R. pseudoacacia plantations occupy large areas in Bulgaria (151,000 ha), France (191,000 ha), Romania (250,000 ha), Ukraine (423,000 ha), Italy (377,000 ha), and Serbia (191,000 ha) (Nicolescu et al. 2018). It is present in 3.35% of Poland's State Forests National Forest Holding stands (Wojda et al. 2015) and has been steadily expanding in Hungary, where it covered around 37,000 ha in 1885 and spread to about 465,000 ha in 2015, amounting to 23.8% of the total forest area (Rédei et al. 2011, Rédei et al. 2015). The species occupies around 41,919,601 ha worldwide (Ciuvăţ et al. 2013). *R. pseudoacacia* is the second hardwood species introduced for wood production in Europe after *Quercus rubra*. In Hungary, it provides 25% of the country's annual wood production (Tobisch and Kottek 2013).

Robinia pseudoacacia L. grows in the following Hungarian regions (Figure 2): between the Danube-Tisza interfluve (in the middle of Hungary) and the northeast of Hungary (Nyírség region). It has also expanded over the south and southwest Transdanubia (the hill ridges of Vas and Zala counties and the hill ridges of Somogy County) (Rédei et al. 2011).

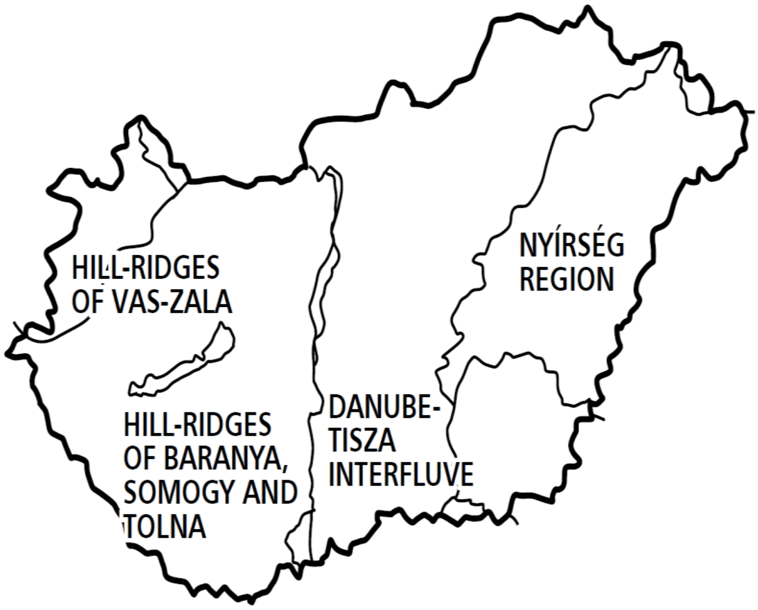


Figure 2: The main Robinia distributions in Hungary (Rédei et al. 2011)

Black locust grows in deep, nutrient-rich, moist, and uncompacted sandy soils, silt, and sandy loams (Rédei et al. 2011). Growth limitations include soil characteristics (compressed soil, oxygen deficiency, wetland (frequent and long-term saturated), climate (late frost damages the leaves and young shoots), competition with other species, and ongoing significant disturbance. Qiu et al. 2010 noted that black locust can enhance the cation exchange capacity of soils and improve organic carbon, total nitrogen, nitrate, carbon, nitrogen, and phosphorus ratios, and the ratios of several enzymes. Nevertheless, *R. pseudoacacia* plantations negatively influence soil moisture recharge at depth (Liang et al. 2022, Li et al. 2022).

Robinia pseudoacacia trees have been tested on high, medium, and low-quality sites in Hungary; however, high-quality wood (and reasonable log dimensions) can be achieved only in areas with sufficient moisture, well-aerated soil, and nutrient-rich, light, humus-rich soils. Black locust forests in locations with medium and poor nutrient content are managed to produce wood fuel, feed, poles, honeybees, soil conservation, and environmental enhancement. *Robinia pseudoacacia* wood has been applied for many purposes, including sawn lumber, adhesive constructions, windows, gates, and agricultural equipment (Molnar, 1995; Enescu and Danescu, 2013; Vasiliki and Ioannis, 2017).

1.3 Characteristics of wood *Robinia pseudoacacia* L.

Robinia pseudoacacia L. is ring-porous (large vessels with circular arrangement) and displays heterogeneous structures (Adamopoulos and Voulgaridis, 2002). As shown in figure 3 the sapwood is formed of two to six annual rings and is bright yellow, while the heartwood ranges in hue from yellow-brown to bluish-gray. The bark is net-like and grayish-brown (Sandor and Mahaly, 2002). *Robinia pseudoacacia* flaws include forked or curved stems – negative for wood production – and frost sensitivity (Podrázský and Prknová, 2019). Yet, its wood properties have been improved through thermal and chemical treatments, as well as advanced wood modification technologies (Kesik et al. 2014; Nemeth et al. 2016; Dzurenda, 2018; Stanciu et al. 2020; Hackenberg et al. 2021; Shapchenkova et al. 2022).

Figure 3: *Robinia pseudoacacia* L. disc

1.3.1 Physical and mechanical properties of wood *Robinia pseudoacacia* L.

Density, moisture content, and shrinkage are the most essential physical characteristics of wood (Shmulsky and Jones 2011). Cell size and cell wall thickness are structural parameters that affect wood density. Consequently, changes in wood structure substantially affect the quality and production of pulp and paper products and the durability and usability of solid wood products. In connection with expected timber use, several mechanical properties characterize wood attributes. Strength and elasticity can be used to characterize wood properties concerning its anticipated usage (Younis et al.

2022). The mechanical properties and their correlations with other features of earlywood and latewood vary, even within the same growth ring (Desch and Dinwoodie 1996).

Stringer and Olson (1987), Sell and Kropf (1990), and other earlier researchers were interested in the basic properties of black locust wood. *Robinia pseudoacacia* wood is dense, brittle, extremely impermeable, and is classified as medium or semi-heavy. It has relatively low shrinkage values but shows poor dimension stability because of fiber slope (a consequence of curved logs). It is more resistant to decay, weather, and insects than most tree species indigenous to Europe (Passialis et al. 2008; Cobas 2018; Podrázský and Prknová 2019). In addition, it has a higher calorific value and ash concentration (Komán 2018). The freshly sawn wood of *Robinia pseudoacacia* contains only about 30% water and burns without initial drying (Wojda et al. 2015, Bijak and Lachowicz 2021).

The literature on black locust reveals that age significantly impacts density, oven-dry density, basic density, porosity, shrinkage, compression strength parallel to the grain, and static bending. Similarly, significant differences in annual ring width, fiber length, and density (basic and oven-dry) of wood were revealed for 10 *Robinia pseudoacacia* clones aged six, eight, and 13 (Klašnja et al. 2000).

Several studies have also investigated the difference in the basic characteristics of *Robinia pseudoacacia* wood within a tree and between different sites (Niklas, 1997; Klisz et al. 2015). According to Klisz et al. (2017), the lower part of the bole has the highest hardness in the longitudinal directions. However, Adamopoulos (2002) revealed no significant difference in radial and tangential modulus of elasticity and rigidity. Analyses of wood samples taken at breast height indicated that specific gravity showed significant radial variation (Stringer and Olson 1987). From the pith, the specific gravity increased radially, rising to 0.68 (average value) near the cambium. A comparison between juvenile and mature wood samples of similar densities revealed that juvenile wood showed significantly lower static bending strength and dynamic strength. The conclusion shows that black locust forests can be efficiently managed to reduce the proportion of juvenile wood by increasing the rotation age (Adamopoulos, 2007).

The mechanical strength and behavior of *R. pseudoacacia* wood collected from plantations in Greece and Hungary appear comparable to beech wood, a species of similar density and widely utilized in the furniture industry. Meanwhile, except for impact bending strength and tangential hardness, the Hungarian *R. pseudoacacia* wood was consistently stronger than materials from Greece. However, both have mechanical strength like beech wood (Kamperidou et al. 2016). *R. pseudoacacia* wood had satisfactory shear bond strength, particularly when using Polyvinyl acetate adhesive and when employing less intensive pressure during the construction of the specimens. However, it is weaker than the same product made from beech (Vasiliki and Ioannis, 2017).

Table 1 in the appendices summarizes the physical properties of *Robinia pseudoacacia* wood in three European countries: Belgium, Hungary, and Poland. Table 2 in the appendices presents various mechanical properties in the same countries. Black locust trees were collected from five sites in Belgium (mixed forests) with silty soil and good drainage to assess physical and mechanical properties. Site factors significantly influenced ring width, axial, tangential, volumetric, and radial shrinkage (Pollet et al. 2012). In Poland, trees of various sizes and ages collected from mixed forests (dominated by black locust) inhabit a transition zone between maritime and continental types in a temperate climate. The most predominant growth conditions are dystrophic and oligotrophic sites developed on rusty, podzolic, and riverine soils. This research investigated the effect of the age and size of trees on their physical and mechanical properties. Age had a substantial impact on most physical and mechanical properties. However, tree diameter had less effect, and no significant effect was observed for latewood proportion, anisotropy, and nearly all shrinkage parameters (Bijak and Lachowicz, 2021). In Greece, naturally grown trees were taken to study the strength properties of juvenile and mature black locust wood. The trees grew under cold winters and relatively warm summers. The findings demonstrate that juvenile wood has significantly lower strength than mature wood, except for axial compressive strength (Adamopoulos, 2007).

1.3.2 Anatomical Features of wood *Robinia pseudoacacia* L.

Wood macroscopic characteristics are information-dense because they technically reveal data about the environmental conditions in which the wood grew. They also hint at its physical traits and contribute to wood identification. Understanding wood's anatomical properties can be vital to selecting the appropriate wood for end use. Anatomical features can be categorized as macro and micro. The macro features include the growth ring and sapwood-heartwood proportion, whereas the micro features include cell characteristics and proportions, pit characteristics, micro-fibril angle, crystals, and vessel inclusions. Usually, the cells of the latewood portions are smaller in radius, have thicker walls, and have smaller lumens, making the tissue dense. (Shmulsky and Jones, 2011).

Juvenile wood (JW) and mature wood (MW) characteristics are used to evaluate wood quality (Bao et al. 2001). Analysis of fiber length and microfibril angle of earlywood and latewood within stems establishes the demarcation between JW and MW (Lu et al. 2021; Wang et al. 2021). Adamopoulos and Voulgaridis (2002) mentioned that the width of the first 5–9 growth rate from the pith of *R. pseudoacacia* is larger and declines gradually. In a vertical variation, the growth rate gradually slowed as the cambium development aged. Stringer and Olson (1987) showed that the radial variability curves are common for cell size (fibers, vessel members), specifically, the fiber length. The wood fiber length increased radially from 0.75 mm in the pith to 1.06 mm in the under-cambium.

The anatomical features (ratios of libriform fiber, vessels, rays, fiber length, vessel member diameter, vessel member length, wide earlywood vessel, and ring width) of *R. pseudoacacia* wood from Hungary, Greece, and Belgium were evaluated from the same material used for physical and mechanical properties (Table 3 in the appendices). The vessel diameter of latewood in Hungarian black locust is larger (more than double) compared to wood from Greece.

1.3.3 Chemical Composition of wood *Robinia pseudoacacia* L.

Wood cell walls contain cellulose, hemicellulose, lignin, and minor quantities of extractives. Cellulose adds to tensile strength, while lignin offers tree stiffness and enables vertical development. Lignin may be removed with chemical or inorganic solvents (Sjöström and Alén, 1998). Extractives are important in hardwood utilization because they prevent deterioration, protect the natural wood color and scent, and enhance grain patterns (Chow et al. 1996; Conners, 2015; Sablík et al. 2016). The extractive content could be removed from a piece of wood using benzene-alcohol, acetone, and organic and inorganic solvents. This varies due to many factors such as extraction process solvent type, wood origin, and type of chemical compounds present in the wood (Desch and Dinwoodie, 1996).

Both benzene-EtOH and total extractive content displayed radial variation in the R. pseudoacacia wood. The outer heartwood tissue held the highest benzene-EtOH content (4.60%) and extractive amounts (8.54%), while the sapwood tissue had the lowest at 2.70 % and 6.8 %, respectively (Stringer and Olson, 1987). Hot water extractives content and lignin in heartwood were higher than in sapwood within *Robinia pseudoacacia* (between heartwood and from bottom to top). Heartwood extractives increased vertically, and lignin decreased from the bottom to the top (Adamopoulos et al. 2005). Phenolic compounds and flavonoids are abundant in the cell walls and cell lumens of axial parenchyma and vessels in the mature heartwood of *Robinia pseudoacacia* (Dünisch et al. 2010). According to chemical analyses (Latorraca et al. 2011), the lack of phenolic compounds and flavonoids in the juvenile heartwood is the primary cause of its reduced durability.

Table 4 in the appendices contains the chemical compositions of *Robinia pseudoacacia* wood grown in Hungary, Bulgaria, Greece, and the Czech Republic. Table 5 in the appendices shows the inorganic constituents of *Robinia pseudoacacia* in Hungary and Greece. The wood and bark of black locust cultivated in Greece and Bulgaria and three clones (NY, U, and J) grown in Hungary were examined (Passialis et al. 2008). Table 4 also lists the range values from the three Hungarian clones.

Researchers examined *Robinia pseudoacacia* wood as a potential chemical pulp and glucose source. They concluded that *Robinia pseudoacacia* clones harvested from plantations in Bulgaria (growing in calcic Chernozem soil) may offer opportunities for chemical pulp or glucose for bioethanol production (Panayotov et al. 2015). Moreover, the impact of *Robinia pseudoacacia* heartwood extractive and bark on the durability of Czech beech wood indicated that black locust heartwood extractive chemicals could raise the native durability of European beech from class five to class three (Sablik et al. 2016).

2 CHAPTER TWO

MATERIALS AND METHODS

2.1 Wood materials and study area

From the bottom and tope of trees, a total of 22 sample logs were obtained from nine locations throughout Hungary (Northern, Central, and Western). These locations presenting five counties as seen in Figure 4. The data on locations, quantity of discs utilized, diameter at breast height, tree growth conditions, and coordinates shows Table 1.

The examined sites were classified into three growth conditions based on soil characteristics: GGC–good growth conditions, PGC–poor growth conditions and MPGC–mixed species under poor growth conditions as defined by Várallyay (2015) and Tóth et al. (2007). The GGC had good quality soil–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. In contrast, the PGC had poor quality soil–rusty brown forest loamy soil with stagnant water about 40–100 cm deep, low fertility, poor structure, compacted, waterlogged, and high salinity. In the MPGC sites, *Robinia pseudoacacia* L. trees grew together with Poplar, Pine, and Oak in PGC. We have not used hybrid varieties for eliminating the resultant variance.

Table 1: County, sites, number of discs, average diameter at breast height (DBH), growth condition and coordinates.

County	Sites within County	Number of disc/sites	Average DBH (cm)	Growth condition	Coordinates
Szabolcs-Szatmár-Bereg	Balotaszállás	2	24.5	GGC	68,6546ºN, 10,9105ºE
	Kunfehértó	3	17	PGC	67,4622ºN, 11,4344ºE
Szabolcs-Szatmár-Bereg	Ófehértó 33	2	26	GGC	87,7527ºN, 29,1922ºE
	Ófehértó 31	2	22	PGC	87,8676ºN, 29,0636º E
	Pap	2	26	GGC	88,1955ºN, 32,1529ºE
	Baktalórántháza	2	27	PGC	87,5568ºN, 29,6031ºE
Vas	Telekes	3	27	MPGC	47,5547ºN, 17,9632ºE
Baranya	Ibafa	1	22	GGC	46,0918ºN, 17,5459º E
	Ibafa	1	20	PGC	
Győr-Moson-Sopron	Iván	2	18	PGC	47,44633ºN, 16,91224ºE
	Iván	2	27	GGC	

***GGCs= good growth conditions; PGCs= poor growth conditions; MPGCs= poor growth conditions (mixed species); the number 31 and 33 in the Ófehértó mean the compartment number inside the forest.

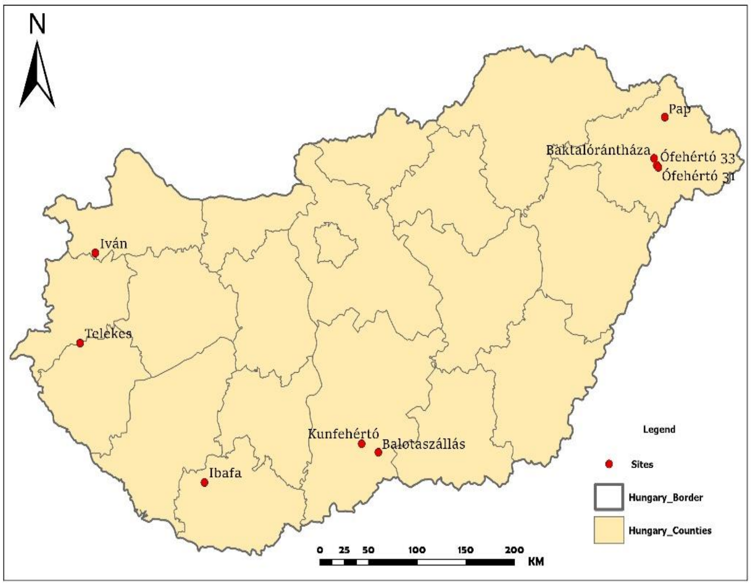


Figure 4: Study area map with specific locations for wood sample collection within the County by name.

2.2 Samples preparation

Three discs, each measuring 4 cm in thickness, were taken from every log at breast height (130–140 cm). One disc was selected for the examination of anatomical features. The second disc was used for chemical composition, whereas the last disc was used for assessing the color parameter.

2.3 Determination of anatomical features *Robinia pseudoacacia* L.

From the first disc, a 2 cm-wide strip was cut from bark to bark and then sliced into two smaller strips, each 2 cm wide and 2 cm thick. The first strips were used to determine out the fiber length (FL), fiber width (FW), fiber wall thickness (FWT), lumen diameter (LD), vessel length (VL), and vessel width (VW) of the wood. The second strips were used to measure the width of the annual rings (Figure 5).

2.3.1 Fiber measurements

The fiber dimensions were assessed for two aims: First, investigate the variability in wood fibers, vessels, and ring width within five counties and three distinctives growth conditions. Second, investigated (1) radial variations in FL, FW, FWT and LD and RW. As well as the relationships between FL and RW with temperature and precipitation of in Bács-Kiskun county.

For the first objective, tiny samples were taken from different locations on the strip. The specimens were positioned in test tubes and macerated with a mixed solution of equal volumes of glacial acetic acid (98%) (Avantor; VWR International Kft) and hydrogen peroxide (30%) (ES Lab Hungary Ltd.), thereafter heated to 65°C for 24–28 hours in a water bath. Subsequently, we cleaned the macerated pieces with distilled water (Franklin, 1945). Following that, a little quantity of the macerated fibers was positioned on glass microscope slides.

The fiber and vessel characteristics were assessed using a light microscope integrated with a digital camera (Nikon Eclipse, Nikon, Japan) and ProScan III software (V31XYZE/D, Prior Scientific Instruments Ltd., Wilbraham Road, Fulbourn, Cambridgeshire, CB21 5ET, UK). A total of fifty wood FL (mm) and twenty-five measurements for FW (μm), FWT (μm), LD (μm), VL (μm), and VD (μm) were obtained from each disc. Similarly, from each annual ring, 50 FL measurements were obtained, while 25 were taken for FW, FWT, and LD. This was done to achieve the second goal.

2.3.2 Ring width measurements

The wood strips were polished using sandpaper to smooth the rough surfaces. The smooth strips were scanned using a scanner (CanonScan LiDE 110, Canon, Japan) (Abràmoff eat al. 2004). Then, the annual ring widths were measured with ImageJ software (V1.54d, National Institutes of health, MD, USA).

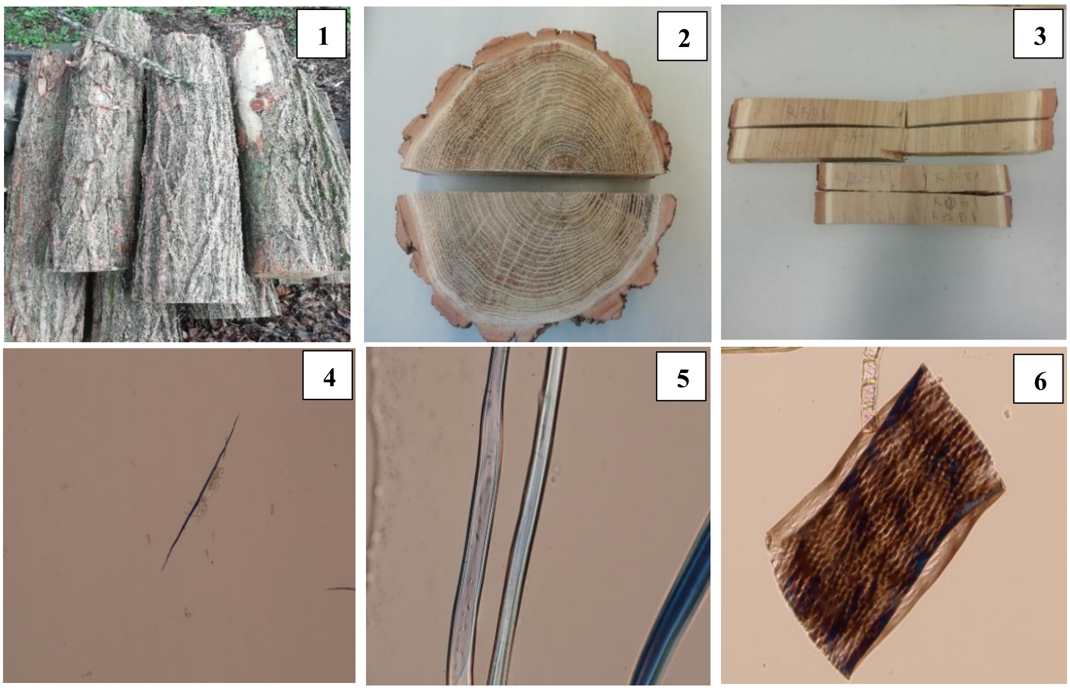


Figure 5: sample image (1) wood material;(2) disc; (3) strips from pith to bark; (4) fiber length (4x lens); (5) fiber width (40x lens); (6) vessel dimensions (20x lens).

2.3.3 Transverse sections

3D imaging was conducted with the TESCAN UniTOM XL (Figure 6) micro-computed tomography (micro-CT) system at the University of Szeged, that used non-destructive scans of 2 x 2 × 5 mm specimens. The UniTOM XL represents cutting-edge micro-CT technology, integrating high-throughput, multi-scale, and dynamic 3D imaging capabilities. Renowned for its rapidity, adaptability, and ability to handle various sample types, it serves as a formidable tool for both research and industrial purposes.

Figure 6: TESCAN UniTOM XL

2.4 Determination of chemical compositions *Robinia pseudoacacia* L.

Wood particle (Figures 7**)** was extracted by using a drill from both juvenile and mature heartwood as determined by Adamopoulos and Voulgaridis (2002)**.**

Figure 7: Wood particles Robinia used for chemical compositions

2.4.1 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 hours. After that, the ash content was calculated by the equation 1 and given as a percentage of the original samples according to EN 14775:2010.

$$A = \frac{G2 - G1}{G \times (100 - N)/100} \times 100 \qquad Equation\ 1$$

Where:

A: ash content (%).

G: weight of wood sample (g).

N: moisture content of sample (%).

G1: weight of empty sample pan (g).

G2: sample pan + ash (g).

2.4.2 Determination of extractives content

The wood particles were ground up using a coffee blender. After that, 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. Then, 20 ml of a methanol-water (1:1, v/v) solvent was added to group A, whereas 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 aluminum foil to reduce solvent evaporation during ultrasonic treatment in a bath for 60 minutes. Following sonication, solid residues were removed from the extract using filter paper. 6 ml of the filtered extract was transferred to the pre-weighted aluminum vessel. The containers with the extracts were maintained at laboratory temperatures for 24 hours to ensure the complete evaporation of the solvents. Lastly, the dried extracts were then weighed to determine the final mass of the dry extract. The total extractives content is given as a percentage of the initial samples. Three replicates were run for each sample to yield methanol-water soluble extract content (MWE) and cyclohexane-ethanol soluble extract content (CYE). The sum of these contents resulted in total extractive content (TEC) (Fodor and Hofmann 2024).

2.4.3 Determination of total polyphenol content (TPC)

TPC was determined with 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 minute, 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 minutes, 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).

2.4.4 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 minutes, 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).

2.5 Determination of physical properties of Wood *Robinia pseudoacacia* L.

2.5.1 Assessment of color parameters

The present study measured transverse surface color, even though tangential surfaces are more common in wood products and are more relevant for visual and commercial uses (Moya 2010). This method was chosen to have data that accurately reflects the material. While earlywood and latewood affect transverse section color, composite measurements give reliable (Hirata et al. 2020). The wood discs were precisely sanded with 180 and 80-grit sandpaper and cleansed with compressed air (Figure 8). 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 20ºC 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 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. 2019).

Figure 8: Color measurement specimens.

2.5.2 Determination of wood density, shrinkage and swelling

From both bottom and top logs, a total of 347 samples, each sized 20 × 20 × 30 mm, were used to evaluate moisture content, basic density, density at 12% moisture content, and linear shrinkage and swelling across all counties, as seen in Figure 9.

Figure 9: Specimens used to determine the densities, moisture content, shrinkage and swelling.

Wood moisture content, basic density (based on oven-dry weight per unit green volume) and density at 12 MC% (air dry density) were determined according to ISO 13061-02: 2017 with Equations 2 and 3, respectively.

$$MC\ (\%) = \frac{Moist\ weight\ -\ Dry\ weight}{Dry\ weight} \times 100 \qquad Equation\ 2$$

$$Density\ \left(\frac{g}{cm^3}\right) = \frac{weight}{volume} \qquad Equation\ 3$$

The radial, tangential and longtudinal shrinkage were calculated acording to ISO 13061-13:2016 (E) by equations 4, 5 and 6, respectively.

Radial shrinkage (βr)

$$\beta r\ \% = \frac{I_{r1} - I_{r2}}{I_{r1}} \times 100 \qquad Equation\ 4$$

Tangential shrinkage (βt)

$$\beta t\ \% = \frac{I_{t1} - I_{t2}}{I_{t1}} \times 100 \qquad \text{Equation 5}$$

Longitudinal shrinkage (βL)

$$\beta L\ \% = \frac{I_{L1} - I_{L2}}{I_{L1}} \times 100 \qquad Equation\ 6$$

Volumetric shrikage (βv)

The volumetric shrinkage calculated by the following equation 7 according to ISO 13061-14:2016 (E).

$$\beta v\ \% = \frac{V_1 - V_2}{V_1} \times 100 \qquad \textit{Equation } 7$$

The swelling of specimens in radial, tangential and longtudinal directions were calculated according to ISO 13061-15:2017 by the following equations 8, 9 and 10, respectively.

Radial swelling (αr)

$$\alpha r\ \% = \frac{I_{r1} - I_{r2}}{I_{r1}} \times 100 \qquad \textit{Equation } 8$$

Tangential swelling (αt)

$$\alpha t\ \% = \frac{I_{t1} - I_{t2}}{I_{t1}} \times 100 \qquad \textit{Equation } 9$$

Longitudinal swelling (αL)

$$\alpha L\ \% = \frac{I_{L1} - I_{L2}}{I_{L1}} \times 100 \qquad \textit{Equation } 10$$

Volumetric swelling (αv)

The total volumetric swelling calculated acording to ISO 13061-16:2017 (E).by equation 11.

$$\alpha v\ \% = \frac{V_1 - V_2}{V_1} \times 100 \qquad \textit{Equation } 11$$

Where:

I_{r1}, It1 and I_{L1}= the dimensions (mm) of green or fully saturated test specimens in radial, tangential and longitudinal directions.

I_{r2}, I_{t2} and I_{L2}= the dimentions (mm) of the test peice at absolutley dry condition (oven-dry).

V_1= volume (cm^3) of green of fully sturated test piece.

V_2= volume (cm^3) of the test peice at absolutly dry condition (oven-dry).

2.6 Determination of mechanical properties *Robinia pseudoacacia* L.

For the mechanical tests the specimens were prepared from the bottom and top logs of the trees similar as densities, shrinkage and swelling.

2.6.1 Determinations of Modulus of elasticity (MOE) and modulus of rupture (MOR)

Samples sizes around 20 × 20 × 300 mm were prepared to evaluate the MOE and MOR. The test specimens were done by INSTRON testing machine according to ISO 13061-4: 2014 and ISO 13061-3: 2014 (Figure 10, 1–2). The specimens were loaded perpendicular to the annual rings. The modulus of elasticity in static bending was calculated using the equation 12 and 13 for modulus of rupture.

$$\text{Modulus of elasticity (Ew)} = \frac{PL^2}{4bh^3\, f} \qquad \text{Equation 12}$$

Where:

P= load equal to the difference between the upper and lower limits of loading, in N;

L= span in mm;

b= breadth of the test piece in mm;

h= height of the test piece in mm;

f= the deflection equal to the difference between result obtained in measuring the deflection at the upper and lower limits of loading, in mm.

$$Modulus\ of\ Rupture\ (MPa) = \frac{3FL}{(2RT)^2} \qquad Equation\ 13$$

Where

L= 240mm.

R= width.

T= thickness.

F=maximum force.

2.6.2 Compressive strength

The compression strength parallel to the grain was obtained according to ISO 13061-17:2017. Samples size of specimens was 20 × 20 × 30 mm (Figure 10. 3–4). The calculation was done using the formula.

$$\sigma\ (MPa) = \frac{Fmax}{R * T} \qquad Equation\ 14$$

where

σ= compressive strength.

F = maximum force.

R = width and T = thickness.

Figure 10: samples of mechanical test 1–2 bending test and 3–4 for compression test

2.7 Climate data

The annual maximum temperature and total precipitation data for three counties were collected from the POWER | Data Access Viewer (nasa.gov) website, based on the growth time of trees within the specific county, as shown in Figure 11. These data were collected to investigate their relationships with fiber length and ring width in Bács-Kiskun (Central Hungary). In addition to their relationships with ring width in Szabolcs-Szatmár-Bereg (Northern) and Győr-Moson-Sopron (Western).

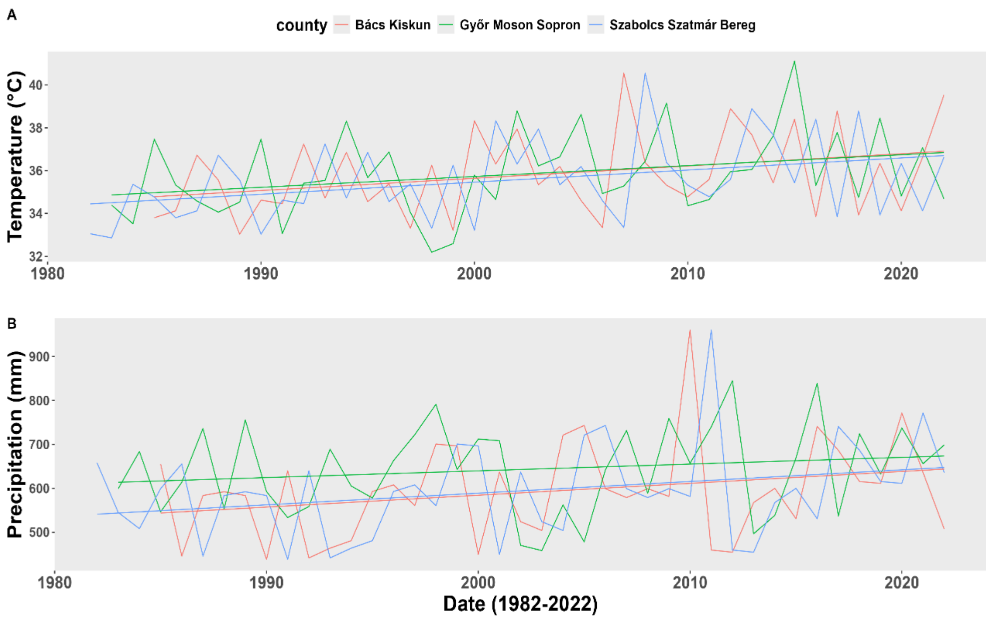


Figure 11: Annual maximum temperature (A) and total precipitation (B) pattern from 1982 to 2022 of Szabolcs-Szatmár-Bereg, Bács-Kiskun, and Győr-Moson-Sopron.

2.8 Data analysis

All data was analyzed using statistical software (R (V4.3.2 (2023-10-31 ucrt) Core Team, RStudio, Inc., Boston, USA). With assistance packages including, ggplot2, ggpubr, ggcorrplot, gridExtra, multcompView, ggthemes, dplyr, and tidyr. The normal distribution of the data was check by Shapiro–Wilk test at first. In case the Shapiro finding shows significant variability, the Kruskal–Wallis nonparametric test was used to determine the statistical significance as an alternative of ANOVA test.). To identify the differences in mean ranks between groups, we used the post hoc test, Dunn pairwise comparison (the Bonferroni method). If the data was normally distributed the ANOVA (analysis of variance) was used, following Tukey's HSD test to investigate the differences between the groups.

Pearson's correlation test was applied to determine the relationships between FL and RW with temperature and precipitation. Moreover, it applied to investigate the relationships between wood color parameters with extractives and total polyphenol contents. As well as the relationship between basic density and mechanical properties.

A dimensionality reduction was carried out using principal component analysis (PCA) on the correlation matrix to clarify the associations between the wood properties of *Robinia pseudoacacia* L., and the corresponding specific site and growth conditions.

3 CHAPTER THREE

RESULT AND DISCUSSION

3.1 Anatomical properties of wood *Robinia pseudoacacia* L.

3.1.1 Fiber properties, vessels length and width and ring width of Robinia wood across Hungarian counties and among the growth conditions

Throughout all counties, the mean ranks of wood FL ranged from 1.04 to 1.11 mm, whereas FW, FWT, and LD ranged from 15.5 to 18.4 µm, 2.55 to 3.76 µm, and 8.19 to 9.98 µm, respectively. The VL, VW, and RW ranged from 118.9 to 126 µm, 191 to 223 µm, and 1.25 to 3.68 mm to 3.90 mm, respectively, as displayed in Table 2. The measurements of VL and VW dimensions were taken from both early and late wood, leading to higher standard deviations.

Significant variances were observed in FL (kw-squared = 12.4, $p = 0.01$), FW (kw-squared = 30.21, $p < 0.0001$), FWT (kw-squared = 85.66, $p < 0.0001$), VW (kw-squared = 14.31, $p = 0.01$), and RW (kw-squared = 195.77, $p < 0.0001$) according to a Kruskal-Wallis test. By contrast, LD and VL did not show any statistically significant differences (kw-squared = 8.59; $p = 0.08$ and kw-squared = 3.87, $p = 0.42$, respectively).

As presented in Table 3, the Dunn test indicated that only Szabolcs-Szatmár-Bereg exhibited a notable higher median FL (1.09 mm) than Vas County (1.02 mm). Similarly, there was a significant difference in VW between Bács-Kiskun and Szabolcs-Szatmár-Bereg. The median values of FW (15.93 µm), FWT (2.78 µm), and RW (1.19 mm) were significantly lower in Bács-Kiskun County than in the other counties.

Table 2: The quantitative statistics of fiber, vessel and ring width of *Robinia pseudoacacia* L. wood across counties.

County	Statistic	FL (mm)	FW (µm)	FWT (µm)	LD (µm)	VL (µm)	VW (µm)	RW (mm)
Szabolcs-Szatmár-Bereg	Mean	1.11	17.6	3.47	8.97	139	177	3.63
	Median	1.09	17.50	3.80	8.18	140.85	172.31	3.12
	Min	0.81	11.87	2.13	5.24	91.07	103.61	1.54
	Max	1.42	21.82	4.83	13.30	202.76	288.95	6.34
	Std	0.13	2.288	0.674	2.13	28.6	42.9	1.34
Bács Kiskun	Mean	1.08	15.5	2.55	8.19	136	242	1.25
	Median	1.07	15.93	2.78	9.05	128.81	271.79	1.19
	Min	0.82	12.95	1.70	5.52	100	107.97	0.30
	Max	1.39	17.63	3.33	9.84	195.76	366.73	2.68
	Std	0.117	1.31	0.332	1.91	28.1	79.9	0.72
Győr-Moson-Sopron	Mean	1.08	17.1	3.24	8.90	118	193	3.21
	Median	1.06	16.86	3.60	8.29	142.71	200.03	3.02
	Min	0.83	12.47	2.24	5.69	82.14	96.69	0.98
	Max	1.37	22.96	4.44	13.13	228.55	299.64	5.95
	Std	0.139	2.71	0.596	2.15	48.5	58.7	1.28
Baranya	Mean	1.06	17	3.30	9.98	144	188	3.11
	Median	1.07	16.13	3.19	8.87	150.43	184.24	3.06
	Min	0.72	11.19	2.08	5.04	91.92	124.18	1.36
	Max	1.47	23.98	4.82	16.59	194.51	283.57	5.09
	Std	0.139	3.71	0.602	2.64	39.1	48.1	1.04
Vas	Mean	1.04	18.4	3.76	9.14	144	179	3.68
	Median	1.02	18.63	3.72	8.89	142.08	171.71	3.91
	Min	0.75	13.46	2.24	5.06	92.43	141.53	1.36
	Max	1.34	22.47	5.06	13.89	196.24	209.66	6.02
	Std	0.155	2.71	0.757	2.40	31.4	26.3	1.25
All	**Mean**	**1.08**	**17.08**	**3.26**	**8.68**	**121.53**	**205.64**	**3.01**
	Std	**0.13**	**2.90**	**0.70**	**2.12**	**44.11**	**93.08**	**1.97**

***Min= minimum; Max= maximum; Std= standard deviation.

Table 3: Post-hoc pairwise comparisons (Bonferroni method) between County groups.

Parameters	Comparison	Z-statistic	Adjusted p-value
FL	Szabolcs-Szatmár-Bereg vs Vas	3.12	0.008
FW	Bács Kiskun vs. Győr-Moson-Sopron	-2.97	0.04
	Bács Kiskun vs. Szabolcs-Szatmár-Bereg	- 4.55	0.0001
	Bács Kiskun vs Vas	-4.63	0.0001
	Baranya vs Vas	-2.92	0.0001
FWT	Bács Kiskun vs Baranya	-5.99	0.0001
	Bács Kiskun vs Győr-Moson-Sopron	-5.54	0.0001
	Bács Kiskun vs Szabolcs-Szatmár-Bereg	-8.44	0.0001
	Bács Kiskun vs Vas	-7.26	0.0001
VW	Bács Kiskun vs Szabolcs-Szatmár-Bereg	3.68	0.001
RW	Bács Kiskun vs Baranya	-7.95	0.0001
	Bács Kiskun vs Győr-Moson-Sopron	-7.99	0.0001
	Baranya vs Szabolcs-Szatmár-Bereg	-11.18	0.0001
	Baranya vs Vas	-11	0.0001

Table 4 shows, the basic statistics for wood fibers, vessels, and annual ring width under the growth conditions. The outcome indicted that GGC produced the longest FL (1.12 mm) and VL (125 µm) and the widest VW (227 µm). Similarly, the FW, FWT, and LD parameters were highest in MPGC. Conversely, most of the parameters were lowest in PGC compared to those observed in other growth conditions.

Table 4: The descriptive statistics of fiber and vessel properties of wood *Robinia pseudoacacia* L. grown at GGC–good growth conditions, PGC–poor growth conditions and MPGC–poor growth conditions mixed species.

Growth conditions	Statistic	FL (mm)	FW (µm)	FWT (µm)	LD (µm)	VL (µm)	VW (µm)	RW (mm)
GGC	Mean	1.12	16.9	3.33	8.34	125	227	3.68
	Median	1.11	16.87	3.21	7.98	143.61	202.98	3.34
	Min	0.80	12.32	1.70	5.04	91.92	103.61	1.05
	Max	1.42	22.96	5.20	13.32	228.55	366.73	5.67
	Std	0.139	2.87	0.745	1.97	43.6	87.9	1.25
PGC	Mean	1.06	17.0	3.09	8.93	118	182	2.70
	Median	1.05	16.29	3.05	8.86	137.04	169.94	2.74
	Min	0.81	11.19	1.65	5.09	82.14	96.69	1.43
	Max	1.39	23.98	4.82	13.80	202.76	299.64	3.81
	Std	0.119	2.93	0.582	2.18	45	95.9	0.67
MPGC	Mean	1.04	18.4	3.76	9.14	122	215	3.68
	Median	1.02	18.44	3.72	8.89	142.08	171.71	3.91
	Min	0.95	13.46	2.24	5.06	92.43	141.53	1.36
	Max	1.34	22.47	5.06	13.89	196.24	209.66	6.02
	Std	0.155	2.71	0.757	2.40	42.2	78.9	1.25

***Min= minimum; Max= maximum; Std= standard deviation.

There were differences in FL (kw-squared = 25, $p < 0.0001$), FW (kw-squared = 8.76, $p < 0.0001$), FWT (kw-squared = 18.50, $p = 0.0001$), VW (kw-squared = 15.64, $p = 0.0001$), and RW (kw-squared = 56.58, $p = 0.0001$) based on the growth conditions, as shown by the Kruskal–Wallis test. The statistics for LD and VL did not show significant differences (kw-squared = 5.81, $p = 0.05$ and kw-squared = 5.17, $p = 0.08$, respectively). The analysis of the statistics for LD and VL did not significantly vary (kw-squared = 5.81, $p = 0.05$ and kw- squared = 5.17, $p = 0.08$, respectively). The significant differences (Dunn test) between group conditions are shown in Table 5.

Table 5: Post hoc pairwise comparisons between GGC–good growth conditions, PGC–poor growth conditions, and MPGC–poor growth conditions mixed species.

Parameters	Comparison	Z-statistic	Adjusted p-value
FL	GGC vs. PGC	4.36	0.0001
	GGC vs. MPGC	3.60	0.0005
FW	GGC vs. PMGC	-2.90	0.005
	MPGC vs. PGC	2.72	0.009
FWT	GGC vs. MPGC	-262	0.01
	GGC vs. PGC	2.50	0.01
	MPGC vs. PGC	4.06	0.0001
VW	GGC vs. PGC	3.9	0.0001
RW	GGC vs. MPGC	-3.89	0.0001
	GGC vs. PGC	4.02	0.0001
	MPGC vs. PGC	7.43	0.0001

The variability in the annual ring width from pith to bark for each county is shown in Figure 12. The curve shows that Bács-Kiskun County has the narrowest annual rings, while those of Szabolcs-Szatmár-Bereg and Vas Counties show the widest width. Regarding growing conditions, MPGC and GGC showed the greatest annual ring widths, respectively. PGC, on the other hand, displayed the narrowest widths (Figure 13).

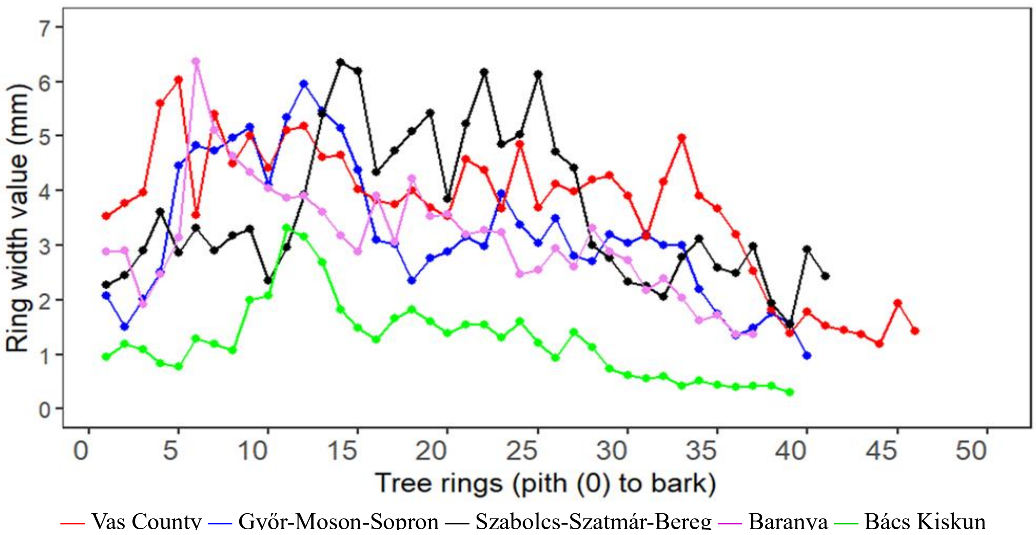
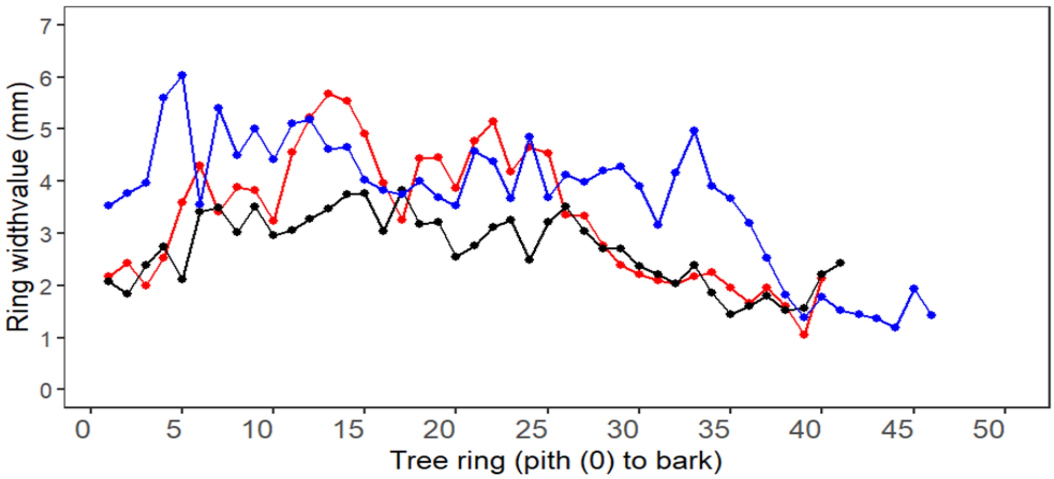


Figure 12: Among County-variability in annual ring width from pith to bark of wood *Robinia pseudoacacia* L.



— GGC–good growth condition — PGC–poor growth condition — MPGC–poor growth condition mixed

Figure 13: Among growth conditions-variability in width of the annual ring from pith to bark of *Robinia pseudoacacia* L. wood.

Robinia pseudoacacia L. trees grow widely around the world, including in Hungary (Rédei et al. 2017). They have been used for several important purposes (Rédei et al. 2008; Sillero et al. 2018). In our study, fibers, vessels, and ring width were investigated in several counties and under different growth conditions. These parameters investigated are crucial for the evaluation of wood characteristics (Zhang et al. 2020; Lozjanin et al. 2024).

Fibers play an important role in determining the mechanical properties of wood, such as strength, flexibility, and durability, which are necessary for applications in construction, furniture production, and tool handles. The characteristics of the vessel influence the porosity and permeability of the wood, which are critical in drying, seasoning, and preservative treatments. In addition, ring width is an indicator of growth rate, which is related to wood density and overall mechanical performance (Jang et al. 2005).

Regarding the variability between sites, our results indicate that significant differences in FL occurred only between Szabolcs-Szatmár-Bereg and Vas Counties, and similarly between Bács-Kiskun and Szabolcs-Szatmár-Bereg for VW. Significant differences were also observed between several counties for FW, FWT, VW, and RW (Table 3). In contrast, there were no significant differences in LD and VL between counties. We found that all counties had almost similar characteristics, except Bács-

Kiskun County, which had the lowest values for FW, FWT, and RW and the highest VW, while Szabolcs-Szatmár-Bereg and Vas Counties had the best characteristics.

Previous studies mentioned that there are many factors that cause variations in wood anatomical features between sites. These factors include the type of soil and its corresponding nutrient and moisture availability (Olson et al. 2018). For instance, water availability significantly determines wood vessel and fiber sizes specifically in *Robinia pseudoacacia* L. (Nola et al. 2020). In dry climates or areas with variable water availability, plants typically develop narrower vessels with thicker walls, which reduces the probability of embolism during drought conditions (Hacke and Sperry, 2001). Conversely, areas with increased and stable water availability can produce larger vessels and fiber diameters (Schreiber et al. 2015; February et al. 1995). Also, under favorable growing conditions, the ring widths increase (Fonti et al. 2010; Sass-Klaassen et al, 2011; Ladányi and Blanka, 2015; He et al. 2023). In addition, genetic adaptations likely interact with environmental pressures to alter traits such as fiber wall thickness, vessel diameter, and ring width in response to specific site conditions (Zobel and van Buijtenen, 1989).

Significant variations in fiber properties and growth rings of *Robinia pseudoacacia* L. wood were observed within a single growth ring (Hejnowicz and Hejnowicz, 1959) and within the radial direction (between early and late wood) (Adamopoulos and Voulgaridis, 2002; Stringer and Olson, 1987). Furthermore, regarding tree ages, old trees had longer fiber lengths than the youngest trees (Klašnja et al. 2000; Kiaei et al. 2016).

In comparison to our findings, the fiber length ranged between 1.04 and 1.11 mm, which is higher than values given by (Klašnja et al. 2000) and lower than values reported by (Hejnowicz and Hejnowicz, 1959) for trees aged 60 and 71 years. In terms of growth conditions, GGC showed the greatest fiber, vessel, and ring widths compared to PGC and MPGC. Interestingly, the MPGC had better parameters than PGC, which indicated that the mixed trees have better properties because of different root structures and canopies, allowing for more efficient use of sunlight, water, and nutrients. These reduce the competition and promote better growth conditions, which can enhance fiber properties and growth rate. Previous research has indicated that high-quality sites yield high-quality timber from *Robinia pseudoacacia* L. (Redei et al. 2008). Our findings confirm this due to the long fibers and wide ring widths. The ring width patterns in our study resemble the curves identified by (Adamopoulos and Voulgaridis, 2002; Adamopoulos et al. 2010; Pollet et al. 2012). The widths of the annual rings decreased from pith to bark, which is attributed to the age of the cambium (ring width diminished as age increased). Other species, such as *Alnus glutinosa*, also display a comparable pattern (Kiaei et al. 2016).

3.1.2 Radial variability in fibers parameters and ring width on Wood of Robinia from Bács-Kiskun county.

Figure 14 demonstrates the radial curves of fiber dimensions from the pith to the bark. FL showed a consistent increase, varying from 0.68 mm in the juvenile zone near the pith to 1.08 mm in the outermost mature wood. FW, FWT and LD exhibited notable radial differentiation, with means ranging from 13.05 to 16.07 µm, 1.87 to 2.65 µm, and 6.52 to 10.63 µm, respectively (Figure 14 a–d). Also, RW increased significantly from 0.54 mm at the pith and 6.37 mm at the bark (Figure 15), indicating the shift from narrow juvenile growth increases to the wider growth rings of mature wood.

The first seven annual rings in FL presented an initial increase, while the next three rings showed a small decline. After this transient zone, FL began to rise slowly and steadily again toward the outer wood. Similar patterns were observed for FW and FWT (Figure 14 b–c), whereas LD displayed ongoing radial variability (Figure 14d). RW, on the other hand, had a quick rise in the pith (the first 5 to 12 rings) that then gradually decreased toward the tree's outer growth ring. Analysis of variance (ANOVA) revealed significant radial variations in fiber properties and RW ($p < 0.001$) (Table 6). Both FL and RW patterns match with previous findings for *Robinia pseudoacacia* L. (Adamopoulos and Voulgaridis, 2002; Dünisch et al., 2010).

The phenomena of radial variation, as examined in prior study by Adamopoulos and Voulgaridis (2002), indicates that climatic conditions affect growth rate and fiber dimensions, particularly resulting in a significant increase in fiber length during the juvenile growth period. Stringer and Olson (1987) and Panshin and De Zeeuw (1980) mentioned that fiber length rises radially from the pith to the cambium, exhibiting considerable variance influenced by growth conditions and tree age.

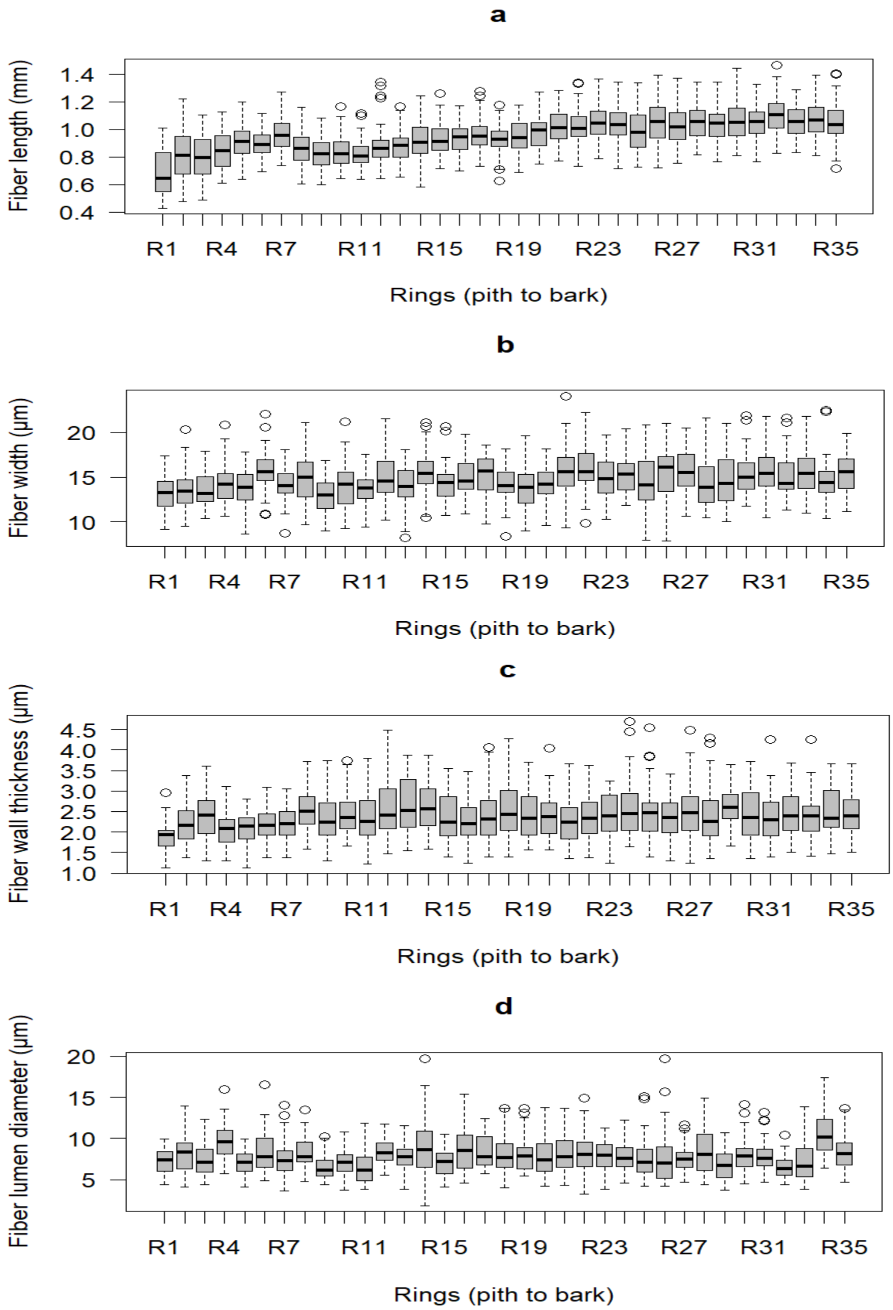


Figure 14: Radial variations in (a) fiber length, (b) fiber width, (c) cell wall thickness, and (d) lumen diameter in *Robinia pseudoacacia* L. wood ºC

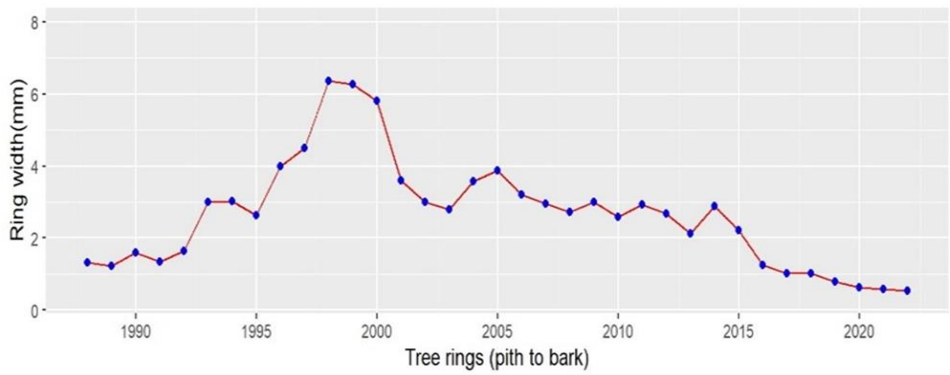


Figure 15: Internal variation in ring width from 1985 to 2022 of *Robinia pseudoacacia* L. wood.

Table 6: Between tree rings variations in fiber properties and ring width (ANOVA test)

Anatomical properties	Sum Sq	Mean Sq	F value	P value
Fiber length (mm)	15.35	0.4515	66.5	0.001
Fiber width (µm)	1053	30.961	5.72	0.001
Fiber wall thickness (µm)	45.8	1.3478	4.39	0.001
Lumen diameter (µm)	1248	36.71	8.13	0.001
Ring width (mm)	29.57	14.79	13.95	0.001

3.1.3 Relationships of climate factors with fiber length and ring width of wood *Robinia pseudoacacia* L. in Bács Kiskun

The relationships between climate factors and FL and RW indicated that the FL and RW were not significantly correlated with precipitation (Figure 16 A–B) and temperature (Figure 16 C–D). Similarly, in Szabolcs Szatmár Bereg (Figure 17) and Győr Moson Sopron counties (Figure 18), the RW was not significantly linked.

Our result is not in line with previous studies, which indicated that precipitation and temperature primary determinants of the functional features in *Robinia pseudoacacia* L. (Song et al. 2013). Also, Kalbarczyk and Ziemiańska (2016) indicated that the ring widths in temperate regions are responsive to winter warmth and July cooling trends, whereas He et al. (2023) highlighted the combined impact of moisture availability, thermal indices, and temperature on radial growth. Also, Govina (2025) found a weak to moderate positive correlation for ring width with precipitation and a negative correlation with the maximum temperature of Turkey oak in Vas County.

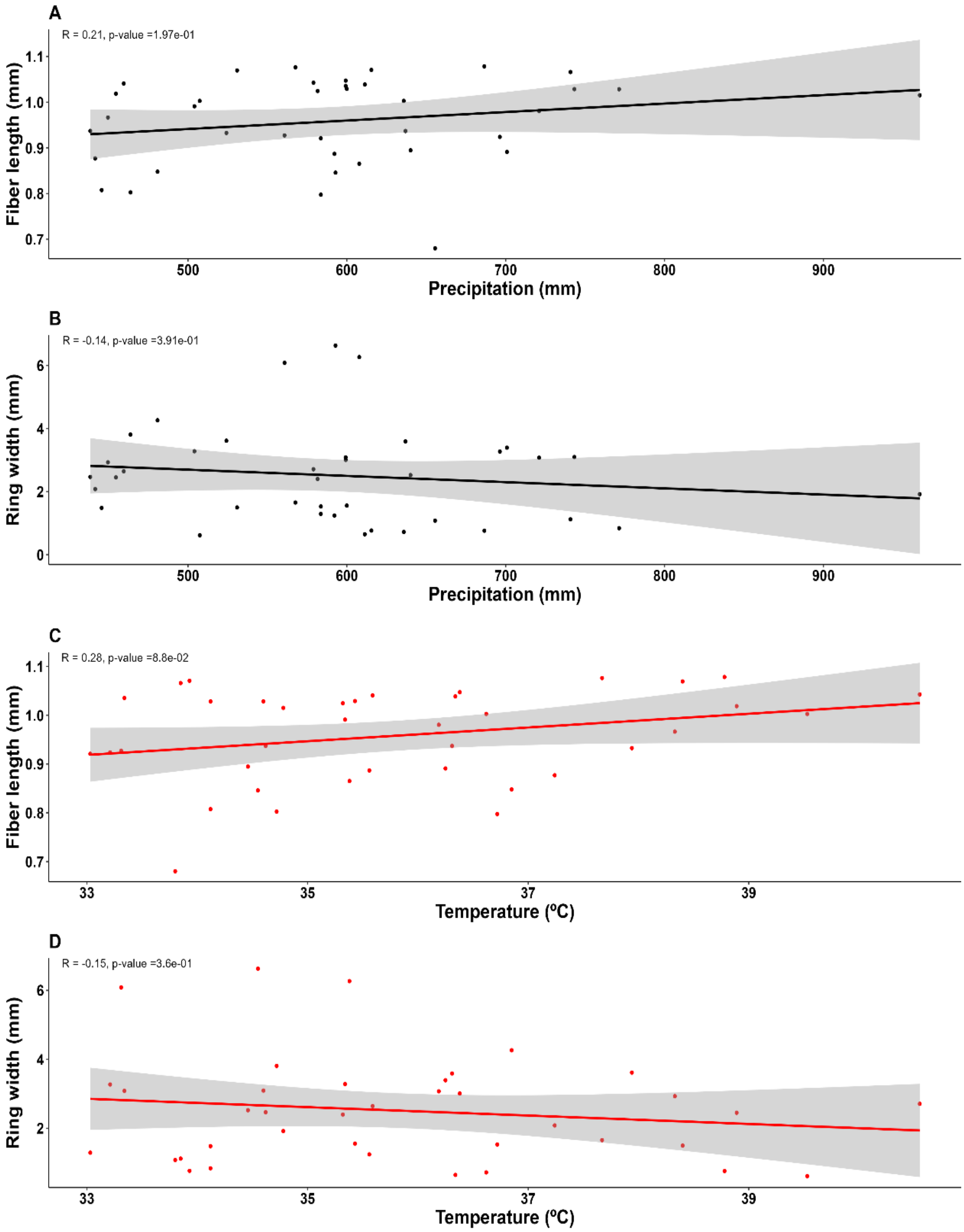


Figure 16: Correlation between fiber length and ring width with precipitation (A and B) and temperature (C and D) of wood *Robinia pseudoacacia* L. from Bács Kiskun county.

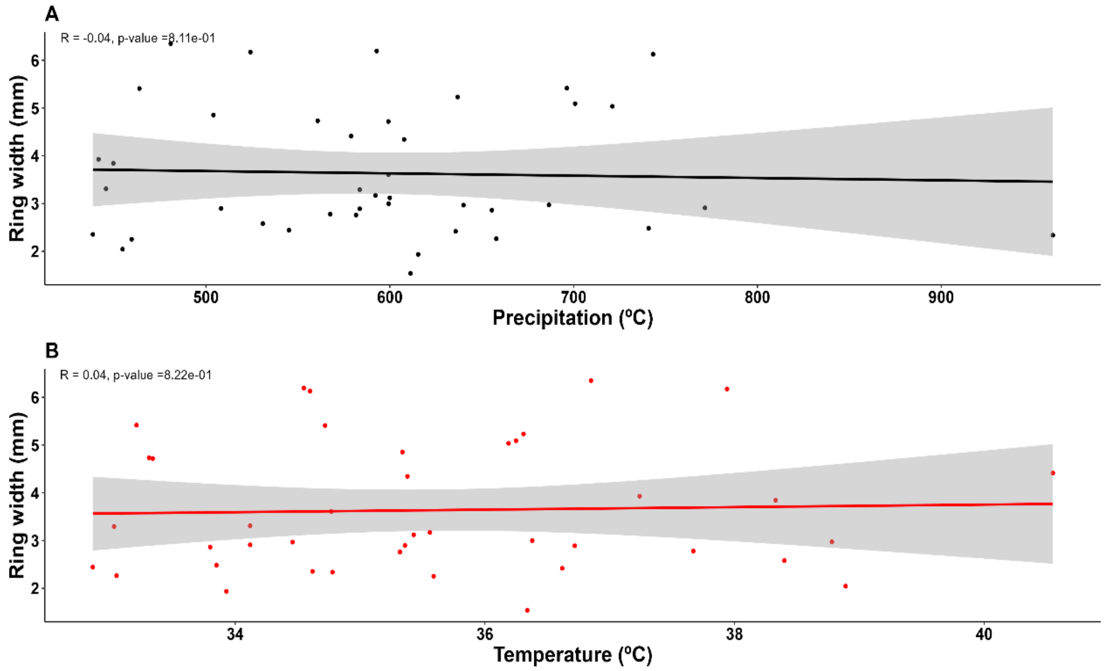


Figure 17: Correlation of precipitation (A) and temperature (B) with FL of wood *Robinia pseudoacacia* L. from Szabolcs Szatmár Bereg.

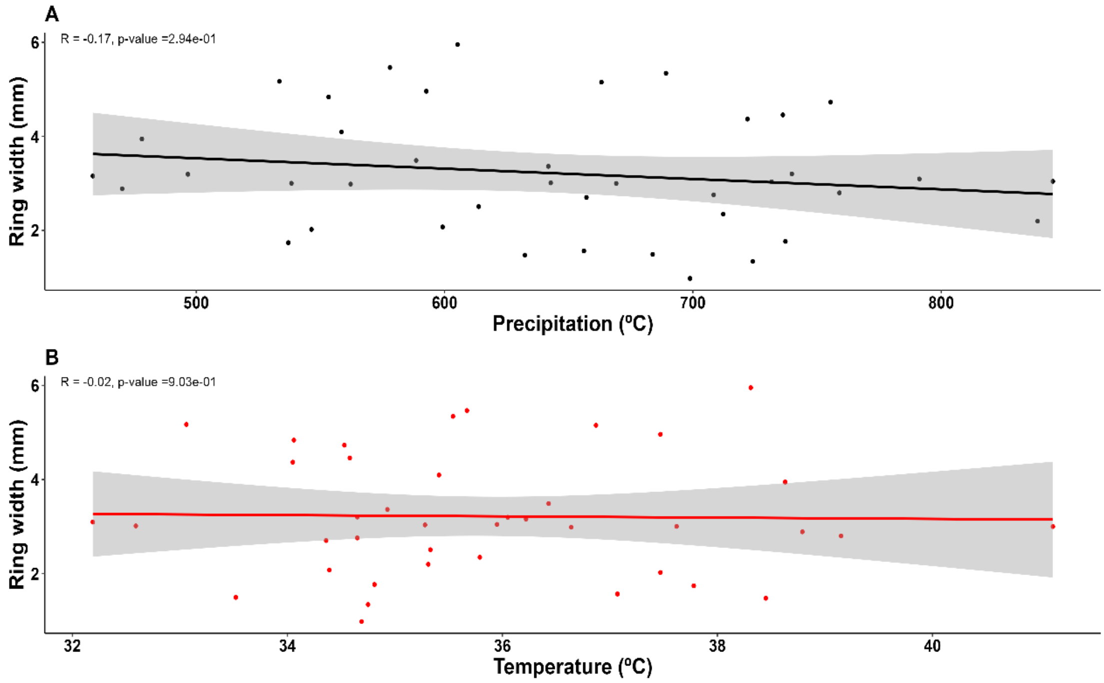


Figure 18: Correlation of precipitation (A) and temperature (B) with FL of wood *Robinia pseudoacacia* L. from Győr Moson Sopron.

3.1.4 Transverse sections of wood *Robinia pseudoacacia* L.

Figure 19 shows the distributions and the variability in vessel diameter across three counties and two growth conditions. From the cross-section of wood Robinia samples from Baranya County from GGC and PGC (Figure 20 A–B, respectively), we note that the crystals are fewer compared with PGC in Szabolcs-Szatmár-Bereg and GGC in Bács Kiskun (Figure 20 C–D, respectively).

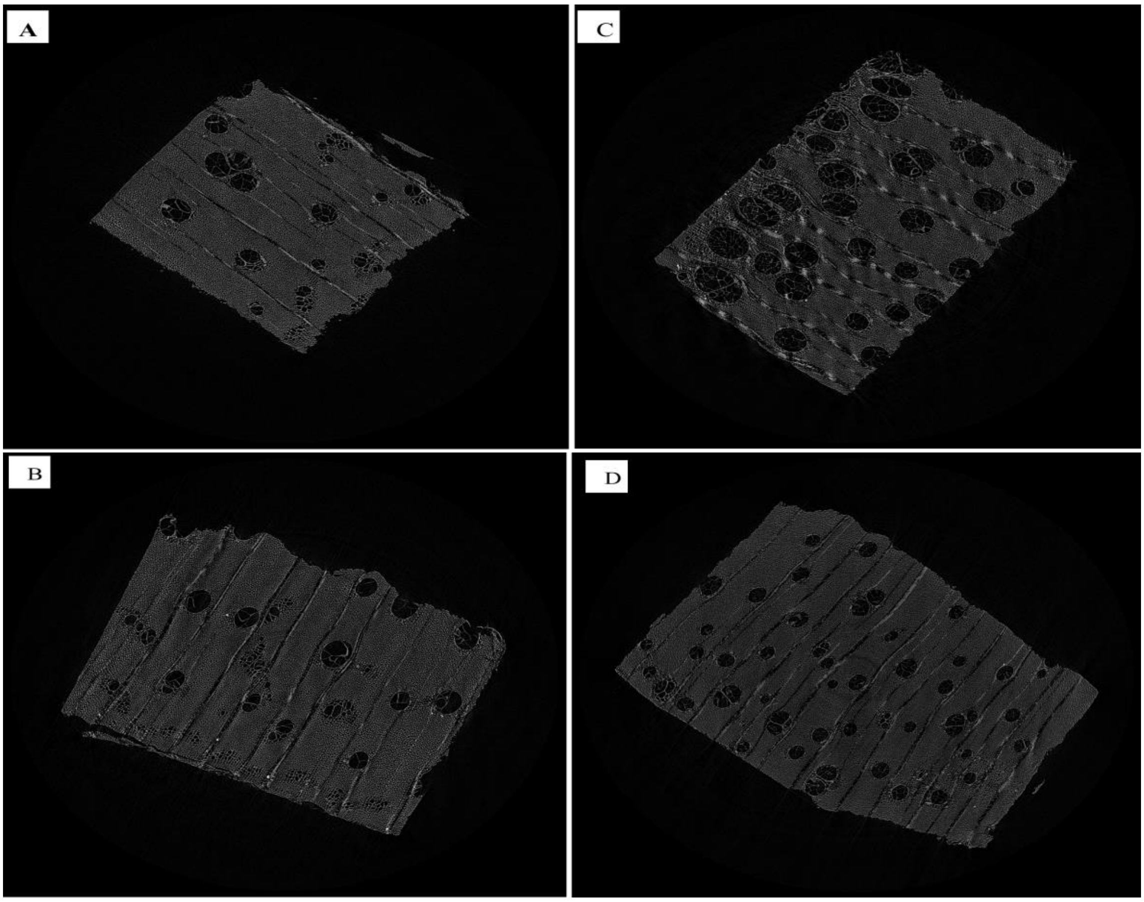


Figure 19: Cross section of Robinia from Baranya County in GGC–good growth condition (A) and PGC–poor growth conditions (B); Szabolcs-Szatmár-Bereg in PGC (C) and Bács Kiskun in GGC(D).

3.2 Chemical Composition of wood *Robinia pseudoacacia* L.

3.2.1 Chemical composition differences across counties and growth conditions

Table 7 presents the average and standard deviation of ash content, extractive content, TPC, and FRAP across counties. The Vas County recorded the greatest values in all variables studied, except that the ash (0.29%) and CYE (1.57%) contents were lowest. Whereas, 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 (Tukey HSD test) in chemical compositions indicated by small letters above the error bar (Figure 20). The uniform letter indicates no significant differences (P≤ 0.05), and vice versa. The ash content and CYE were not significantly varied across counties.

Table 7: Average and standard deviation (Std) of chemical composition of wood *Robinia pseudoacacia* L. across Hungary

County	Ash (%)	MWE (%)	CYE (%)	TEC (%)	TPC GAE/g/dw)	FRAP (mg AA/g dw)
Győr Moson Sopron	0.47 ± 0.10	9.35 ± 0.20	1.60 ± 0.26	10.9 ± 0.331	28.4 ± 2.58	14.7 ± 0.34
Bács Kiskun	0.41 ± 0.09	7.69 ± 0.64	3.42 ± 0.72	11.1 ± 0.45	24.4 ± 1.28	11.1 ± 1.73
Baranya	0.31 ± 0.07	5.04 ± 0.74	2.33 ± 1.72	7.37 ± 2.26	15.1 ± 3.70	6.03 ± 1.87
Szabolcs Szatmár Bereg	0.31 ± 0.15	7.37 ± 2.20	2.23 ± 0.94	9.61± 1.88	25.2 ± 5.32	11.5 ± 2.81
Vas	0.29 ± 0.19	11.8 ± 1.15	1.57 ± 0.76	13.4 ± 1.90	36.0 ± 0.66	17.8 ± 0.42
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.

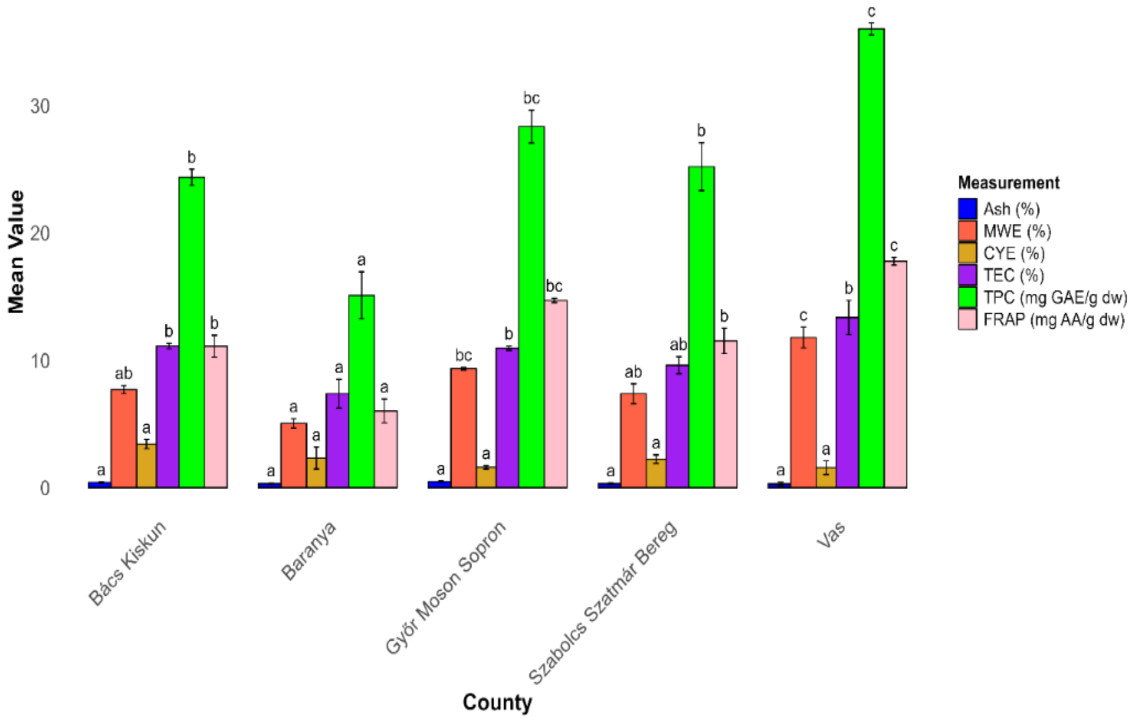


Figure 20: Variation in inorganic and organic extractive composition of wood *R. pseudoacacia* L. across Hungary. Different letters and letter combinations for a given measurement indicate significantly different mean values at p<0.05 level. Error bars indicate standard deviation. Total extractive content was calculated as the sum of MWE and CYE contents. MWE= extractives from methanol-water; CYE= cyclohexane-ethanol.

Among the growth conditions, the average and Standard deviation of chemical compositions of wood *Robinia pseudoacacia* L. are presented in Table 8. While Figure 21 shows their variability. The ash content ranged from 0.29% in MPGC to 0.38% in PGC, while CYE and TEC varied from 1.57% in MPGC to 2.53% in GGC, and from 9.41% in PGC to 13.4% in MPGC, respectively.

Previous studies indicate significant variation in ash content, extractives, pH, and TPC across vertical (from bottom to top) and radial (sapwood to heartwood) orientations in the wood of *Robinia pseudoacacia* L. (Olson 1987; Adamopoulos and Voulgaridis, 2005; Sergent et al. 2014; Vek et al. 2020; Hofmann et al. 2024). Moreover, Passialis et al. (2008) noted substantial differences in chemical constituents across different locations (Greece, Bulgaria, and Hungary). Brischke et al. (2024) conducted a comparison involving Germany, France, Romania, and the United States. However, our findings revealed no significant differences in ash content and CYE among the counties. Correspondingly, the growth conditions revealed no significant differences in ash, CYC and TEC, but they did show significant variances in the other variables.

Table 8: Growth conditions- average and (Std) of chemical composition of wood *R. pseudoacacia* L.

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

***MWE= extractives in methanol/Water; CYE= extractives in Cyclohexane-Ethanol; TEC= total extractives content; TPC= total phenol content; FRAP= Ferric Reducing Antioxidant Power; GGC= good growth conditions; PGC= poor growth conditions; MPGC= poor growth conditions (mixed species)

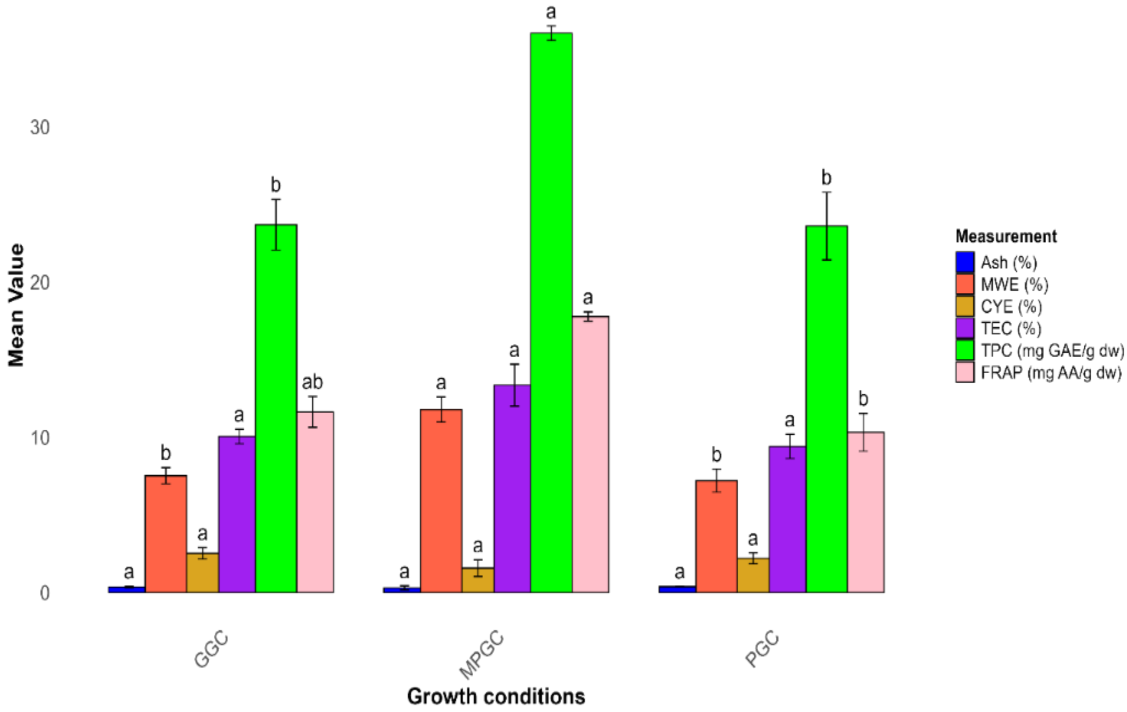


Figure 21: Variation in organic and inorganic composition of wood *Robinia pseudoacacia* L. from GGC–good growth conditions, PGC–poor growth conditions and MPGC–poor growth conditions mixed species in Hungary. Different letters and letter combinations for a given measurement indicate significantly different mean values at p<0.05 level. Error bars indicate standard deviation.

3.3 Physical properties of wood *Robinia pseudoacacia* L.

3.3.1 Color parameters differences across counties and growth conditions

Within counties, the averages and Std of wood color are presented in Table 9. The L* spanned from 56.2 in Baranya to 62.0 in Vas. While a* ranged from 2.64 in Győr-Moson-Sopron to 4.25 in Szabolcs-Szatmár-Bereg. The b* ranged from 26.3 in Szabolcs-Szatmár-Bereg to 30.2 in Győr-Moson-Sopron. The significant differences in color parameters observed between counties are presented in Figure 22.

Table 9: Average and standard deviation (Std) of color parameters of wood *Robinia pseudoacacia* L. for five Hungarian counties

County	L*	a*	b*
Vas	62.0 ±3.15	2.83 ± 1.32	27.8 ± 2.68
Győr Moson Sopron	59.4 ± 4.78	2.64± 1.38	30.2 ± 3.07
Szabolcs Szatmár Bereg	57.6 ± 5.45	4.25 ± 1.39	26.3 ± 2.29
Bács Kiskun	56.8 ± 7.73	3.30 ± 1.63	28.0 ± 4.83
Baranya	56.2 ± 3.14	3.44 ± 1.46	27.6 ± 2.77
All	**57.94 ± 5.55**	**3.51 ± 1.56**	**27.70 ± 3.41**

***L*= lightness; a*= redness; b*= yellowness

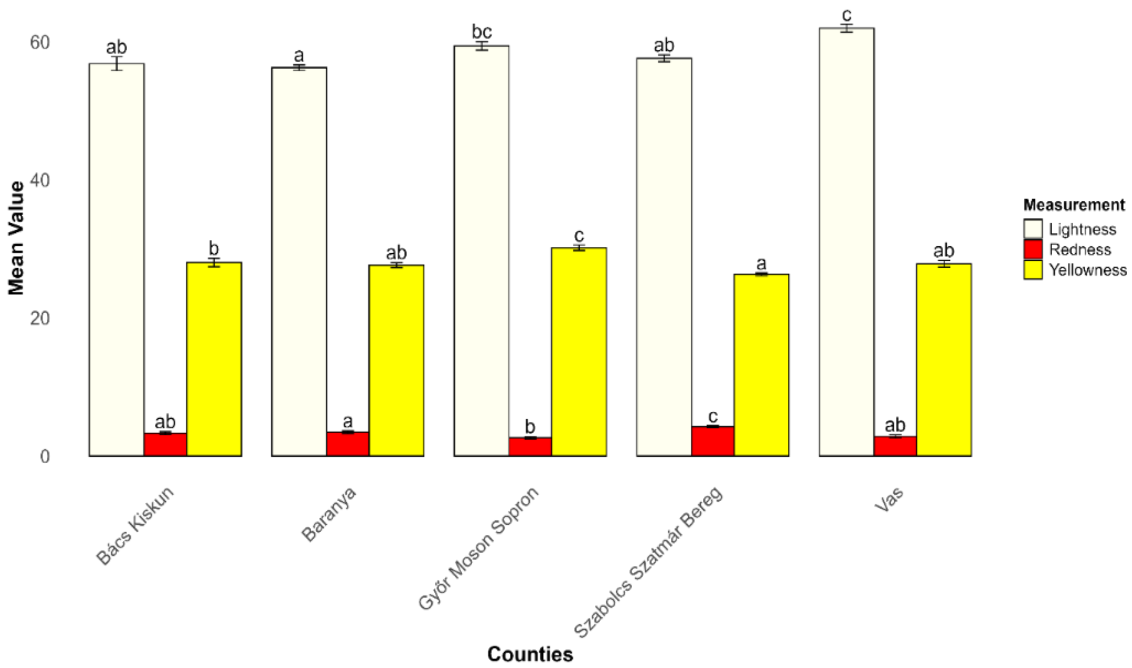


Figure 22: Variation in color parameters lightness, redness and yellowness of wood *R. pseudoacacia* L. across Hungary. Different letters and letter combinations for a given measurement indicate significantly different mean values at p<0.05 level. Error bars indicate standard deviation.

With an average value of 62, MPGC had the highest L* among the growth conditions. Conversely, PGC displayed the lowest value, averaging 56.15. While the a* and b* were intense in PGC with an average value of 3.76 and 28.32, respectively as given in Table 10. 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 conditions. However, the a* differs only between PGC and MPGC. In line, the b* differs between PGC and GGC (Figure 23).

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. The researchers indicated that variation in wood color is due to multiple factors, such as tree species, genetic resources, and silvicultural management (Nishino et al. 1998; Moya and Berrocal, 2010).

Table 10: Growth conditions-average and standard deviation of color parameters of wood *Robinia pseudoacacia* L.

Growth conditions	L*	a*	b*
GGC	58.92±5.89	3.39±1.52	27.05±3.75
PGC	56.15±4.90	3.76±1.61	28.32±3.06
MPGC	62±3.15	2.83±1.32	27.84±2.68

***L*= lightness; a*= redness; b*= yellowness; GGC–good growth conditions; PGC–poor growth conditions; MPGC–poor growth conditions mixed species

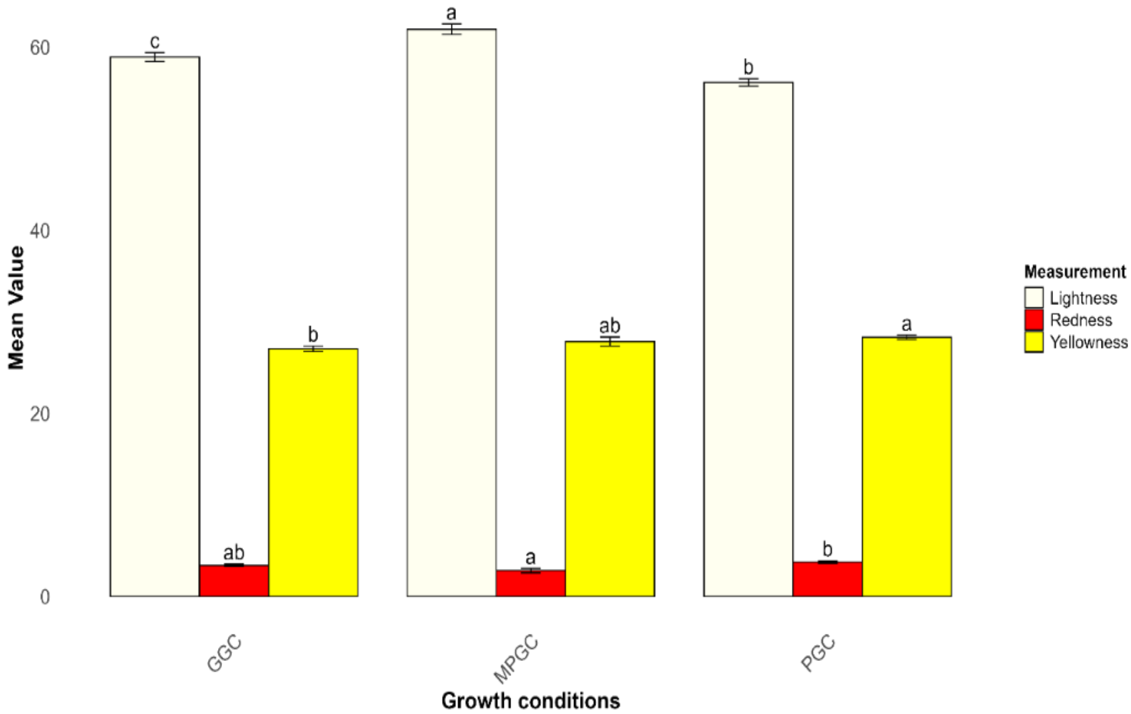


Figure 23: Variation in color parameters (a) lightness, (b) redness, (c) yellowness from GGC–good growth conditions, PGC–poor growth conditions and MPGC–poor growth conditions mixed species in Hungary. Different letters and letter combinations for a given measurement indicate significantly different mean values at p<0.05 level. Error bars indicate standard deviation.

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

Table 11 highlight the correlation coefficients between the color parameters and MWE, CYE, TEC, and TPC. The findings indicated a significant positive correlation between MWE and TPC with L ($r = 0.55$, $p < 0.01$) and ($r = 0.48$, $p < 0.05$), respectively. On the other hand, CYE demonstrated a negative correlation with L* ($r = -0.52$, $p < 0.05$) and b* ($r = -0.59$, $p = 0.01$), while it was positive with a* ($r = 0.47$, $p < 0.05$). In contrast, no significant correlations were observed between TEC and any of the color parameters. Researcher found that *Acacia mangium* and *Vochysia guatemalensis* exhibited distinct performance characteristics (Moya et al. 2012). In larch trees, the a* exhibited a strong correlation with HWE and phenol content; however, this investigation did not identify any correlation (Gierlinger et al. 2004).

The chemical composition (organic and inorganic) and color parameters of wood from *Robinia pseudoacacia* L. can vary within and between trees considerably based on environmental factors, including site conditions such as climate, soil type, and altitude, as well as the age of trees, growth rate, and forest management, in addition to the genetic diversity (Passialis et al. 2008; Dünisch et al. 2010; Sergent et al. 2014; Wei et al. 2017; Németh et al. 2018; Vek et al. 2020). Both chemical compositions and color properties are important quality indicators concerning commercial processes and consumer preferences.

Table 11: 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

3.3.3 Across counties-variability in air dry density and basic density of Robinia wood

Table 12 presents the summary statistics for the air-dry density or density at 12 MC% (ADD) and basic density (BD) of *Robinia pseudoacacia* L. across Hungarian counties. Bács-Kiskun County demonstrated the greatest mean values for AAD at 0.84 g/cm³ and BD at 0.75 g/cm³, whilst Baranya presented the lowest values, at 0.73 and 0.64 g/cm³, respectively.

The Kruskal–Wallis test indicated substantial variations in wood densities among the counties as displayed in Figure 24 A–B. The kw-squared was 118.84 for ADD and 123.01 for BD. Group differences are indicated by letters adjacent to the medians which same letters signify no significant difference, while different letters indicate significant differences at $P < 0.05$ as shown in Table 12.

Table 12: Summary statistic of density at 12 MC% (ADD) and basic density (BD) from five Hungarian counties

County	No	Statistic	ADD (g/cm³)	BD (g/cm³)
Szabolcs-Szatmár-Bereg	82	Mean	0.78	0.69
		Median	0.78 [b]	0.69 [c]
		Std	0.05	0.04
		Min	0.67	0.60
		Max	0.89	0.79
Bács Kiskun	77	Mean	0.84	0.75
		Median	0.84 [a]	0.75 [a]
		Std	0.05	0.04
		Min	0.72	0.63
		Max	0.94	0.86
Győr-Moson-Sopron	75	Mean	0.82	0.72
		Median	0.81 [a]	0.71 [b]
		Std	0.07	0.06
		Min	0.69	0.61
		Max	0.95	0.85
Baranya	55	Mean	0.73	0.65
		Median	0.73 [c]	0.64 [d]
		Std	0.04	0.04
		Min	0.61	0.58
		Max	0.85	0.77
Vas	58	Mean	0.76	0.66
		Median	0.76 [c]	0.67 [d]
		Std	0.05	0.04
		Min	0.53	0.49
		Max	0.87	0.79
All	347	Mean	0.80	0.71
		Std	0.07	0.06

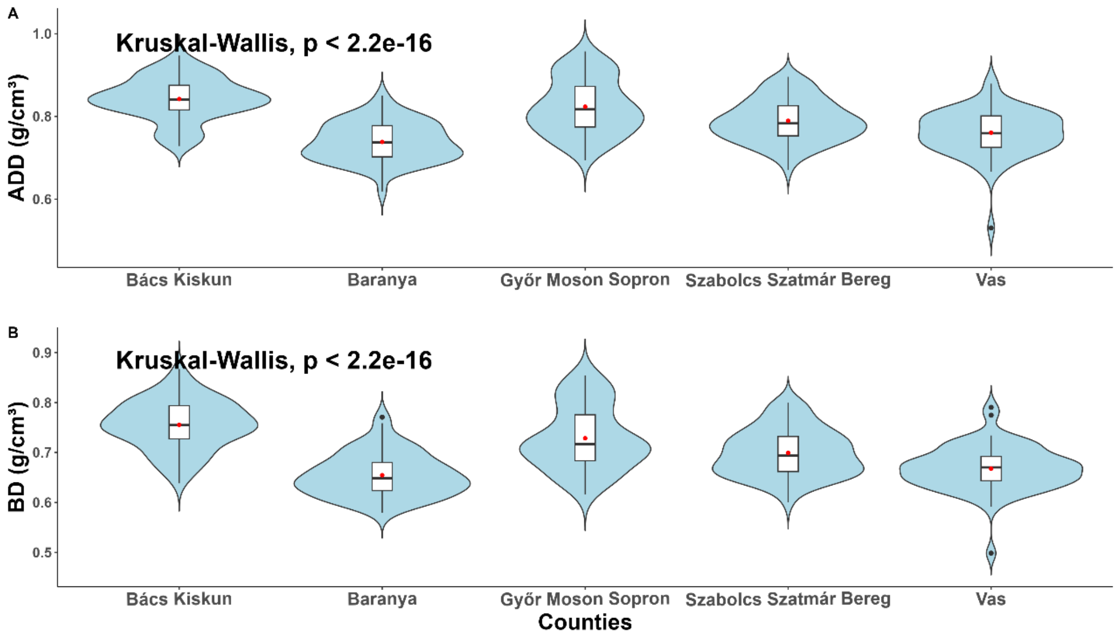


Figure 24: Visualization of (A) air dry (ADD) and (B) basic (BD) densities within counties and the Kruskal-Wallis test showing the significant at $p<0.05$.

3.3.4 Among the growth conditions variability in air dry and basic densities of Robinia wood

Significant differences were found in ADD and BD across the growth conditions, as shown in Figure 25 A–B, respectively. The kw-squared = 27.469 for ADD and 31.27 for BD. the difference between groups indicated by letters as proven in Table 13. Which similar letters denoted no significant difference, but different letters signify significant changes at $P < 0.05$. The PGC exhibited the highest average values 0.81 g/cm³ for ADD and .72 g/cm³ for BD, while the MPGC recorded the lowest values at 0.76 and 0.67 g/cm³, respectively.

When compared with values 734 $kg.m^{-3}$ for density at 12 MC% and 606 $kg.m^{-3}$ for BD reported by Pollet et al. 2012 in Belgium, our findings cross all counties and growth conditions consistently exhibited higher density values. Bijak and Lachowicz (2021) indicated that the variability in wood density of Robinia attributed to the trees age and size diameter. The tree with age of 38 years old revealed highest basic density with value of 824.4 734 $kg.m^{-3}$ than 706.3 $kg.m^{-3}$ for 60 years old and 668.5 $kg.m^{-3}$ for 71 years old. The thinnest trees observed highest densities. In this study the tree age is vary from 33 to 45 years as well the diameters at breast height (Figure 12 and Table 1). Therefore, the variability in densities it could be to the same factors mentioned in addition to the growth conditions.

Table 13: Basic statistic of air-dry density (ADD) and basic density (BD) among three growth conditions

Growth conditions	No	Statistic	ADD (g/cm³)	BD (g/cm³)
GGC	139	Mean	0.79	0.70
		Median	0.78 [b]	0.69 [b]
		Std	0.05	0.05
		Min	0.69	0.59
		Max	0.94	0.87
PGC	150	Mean	0.81	0.72
		Median	0.817 [a]	0.72 [a]
		Std	0.07	0.07
		Min	0.62	0.58
		Max	0.96	0.85
MPGC	58	Mean	0.76	0.67
		Median	0.76 [c]	0.67 [c]
		Std	0.05	0.04
		Min	0.53	0.49
		Max	0.87	0.79

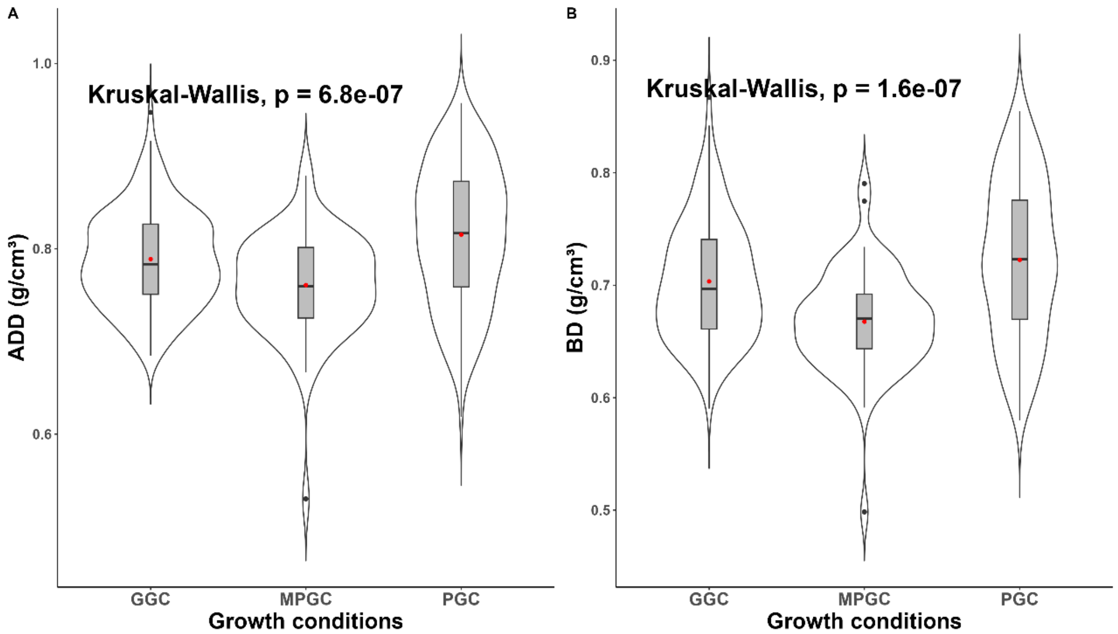


Figure 25: Visualization of (A) air dry density (ADD) and (B) basic density (BD) data under the growth conditions and the Kruskal-Wallis test showing the significant at $p< 0.05$.

3.3.5 Inter-county variability in the linear and volumetric shrinkage and swelling of Robinia wood

Table 14 summarizes the descriptive statistics for shrinkage and swelling. Among the counties, Bács-Kiskun exhibited the lowest mean values for RSH, TSH and VSH, with averages of 4.13%, 4.78%, and 9.31%, respectively. While that Vas County reveal the highest linear and volumetric shrinkage. Likewise, Bács-Kiskun showed the smallest means for RSW, TSW and VSW, measuring 5.48%, 7.06%, and 13.8%, respectively. while that Győr Moson Sopron County recorded the greatest values.

Statistically, significant variations in linear and volumetric shrinkage and swelling were observed among the counties, apart from LSW, which did not differ significantly (Figures 26 and 27, respectively). The kw-squared was 32.448 for SHR, 41.588 for SHT, 64.728 for SHL and 64.314 for SHV. While that 17.525, 52.285 and 37.144 for SWR, SWT and SWV, respectively. Differences among specific groups are indicated in Table 14 by the lowercase letters displayed above the medians.

Table 14: Basic statistic of shrinkage and swelling of wood *Robinia pseudoacacia* L. from five Hungarian counties

County	No	Statistic	RSH %	TSH %	LSH %	VSH %	RSW %	TSW %	LSW %	VSW %
Szabolcs-Szatmár-Bereg	82	Mean	4.47	5.43	0.61	10.2	6.08	8.07	0.80	15.6
		Median	4.36^{ab}	5.67^{b}	0.52^{a}	10.4^{b}	5.99^{ab}	8.16^{bc}	0.75^{ns}	15.6^{bc}
		Std	0.97	1.29	0.36	1.85	1.46	1.82	0.36	3.47
		Min	2.06	2.18	0.01	5.43	3.51	4.91	0.12	9.01
		Max	7.49	8.30	1.73	14.4	10.7	12.1	1.65	23.7
Bács Kiskun	77	Mean	4.13	4.78	0.71	9.31	5.48	7.06	0.81	13.8
		Median	4.11^{a}	4.80^{a}	0.68^{a}	9.27^{a}	5.35^{a}	7.10^{a}	0.64^{ns}	13.3^{a}
		Std	0.75	0.84	0.35	1.26	1.29	1.08	0.45	2.42
		Min	2.57	0.90	0.20	4.76	2.38	4.25	0.21	9.79
		Max	6.18	6.48	1.63	13.9	8.89	9.60	1.97	19.4
Győr-Moson-Sopron	75	Mean	4.58	5.41	0.67	10.3	6.17	8.67	0.77	16.4
		Median	4.47^{bc}	5.40^{b}	0.60^{a}	10.5^{b}	6.07^{b}	8.71^{c}	0.54^{ns}	15.8^{c}
		Std	0.78	0.76	0.41	1.26	1.24	1.31	0.51	2.97
		Min	2.54	3.45	0.10	6.94	3.76	6.12	0.19	10.8
		Max	6.35	7.19	2.90	12.8	9.03	12.1	1.97	23.5
Baranya	55	Mean	5.52	5.37	0.62	10.1	5.62	7.98	0.73	14.8
		Median	4.48^{ab}	5.52^{b}	0.72^{a}	10.2^{b}	5.21^{ab}	7.57^{b}	0.73^{ns}	14.1^{ab}
		Std	0.88	0.99	0.25	1.61	1.12	1.42	0.26	2.62
		Min	2.27	3.44	0.11	6.31	4.02	5.11	0.28	10.4
		Max	6.34	7.24	0.98	13.7	9.26	11.1	1.78	19.3
Vas	58	Mean	5.12	5.93	1.62	11.9	6.15	8.35	0.76	15.9
		Median	4.99^{c}	5.83^{b}	1.22^{b}	11.4^{c}	6.09^{b}	8.41^{bc}	0.75^{ns}	16.0^{bc}
		Std	1.04	1.17	0.09	2.00	1.49	1.39	0.26	2.51
		Min	2.99	2.03	0.19	6.54	1.58	3.78	0.05	10.3
		Max	7.58	8.57	3.89	15.9	10.6	11.6	1.57	21.4
All		Mean	4.54	5.35	0.82	10.28	5.91	8.01	0.78	15.29
		Std	0.94	1.09	0.66	1.79	1.37	1.54	0.40	2.99

***RSH= radial shrinkage; TSH= tangential shrinkage; LSH= longitudinal shrinkage; VSH= volumetric shrinkage; RSW= radial swelling; TSW= tangential swelling; LSW= longitudinal swelling; VSW= volumetric swelling.

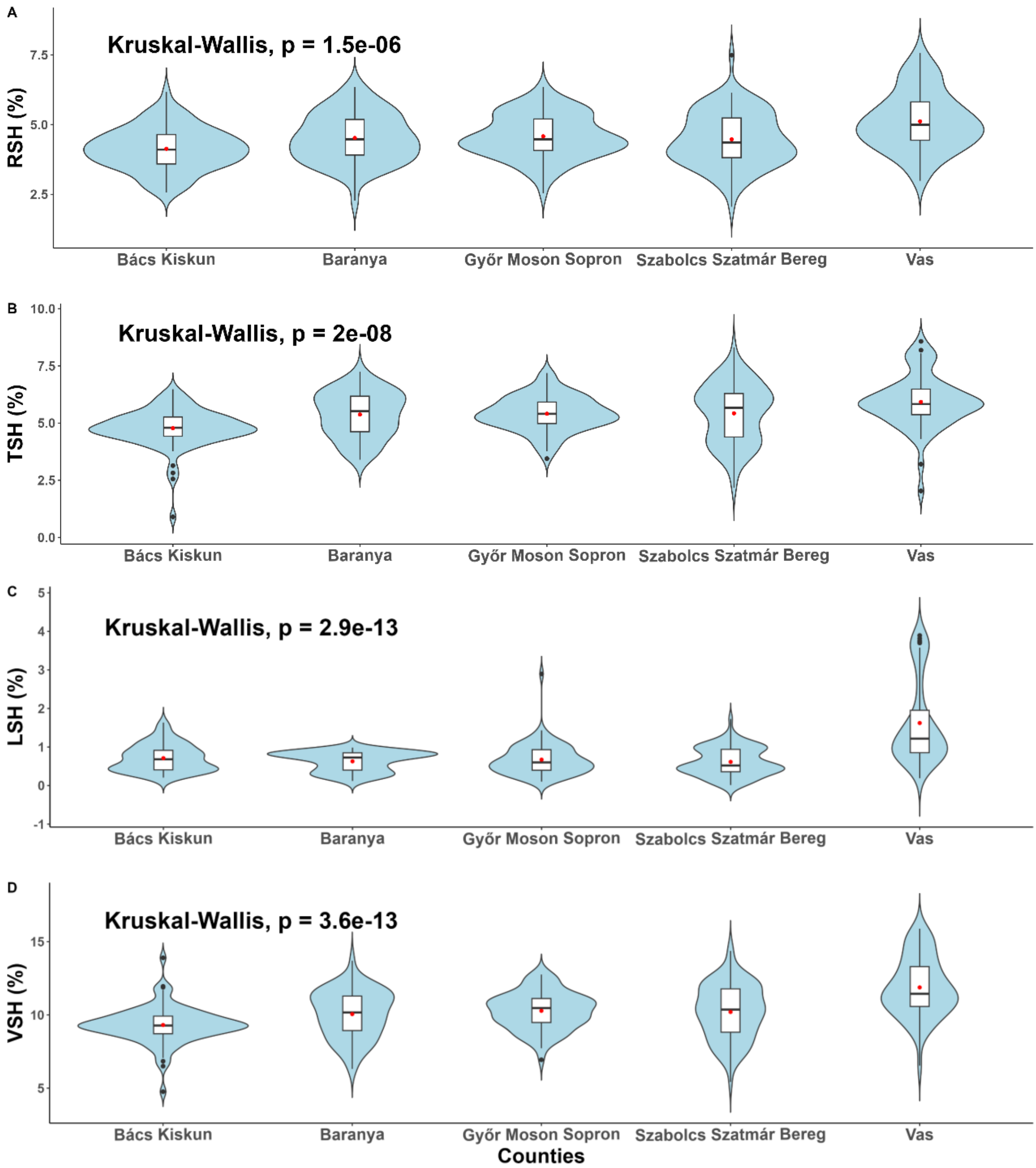


Figure 26: Data visualization of shrinkage for counties. (A) radial shrinkage (RSH); (B) tangential shrinkage (TSH); (C) longitudinal shrinkage; (D) volumetric shrinkage (VSH)

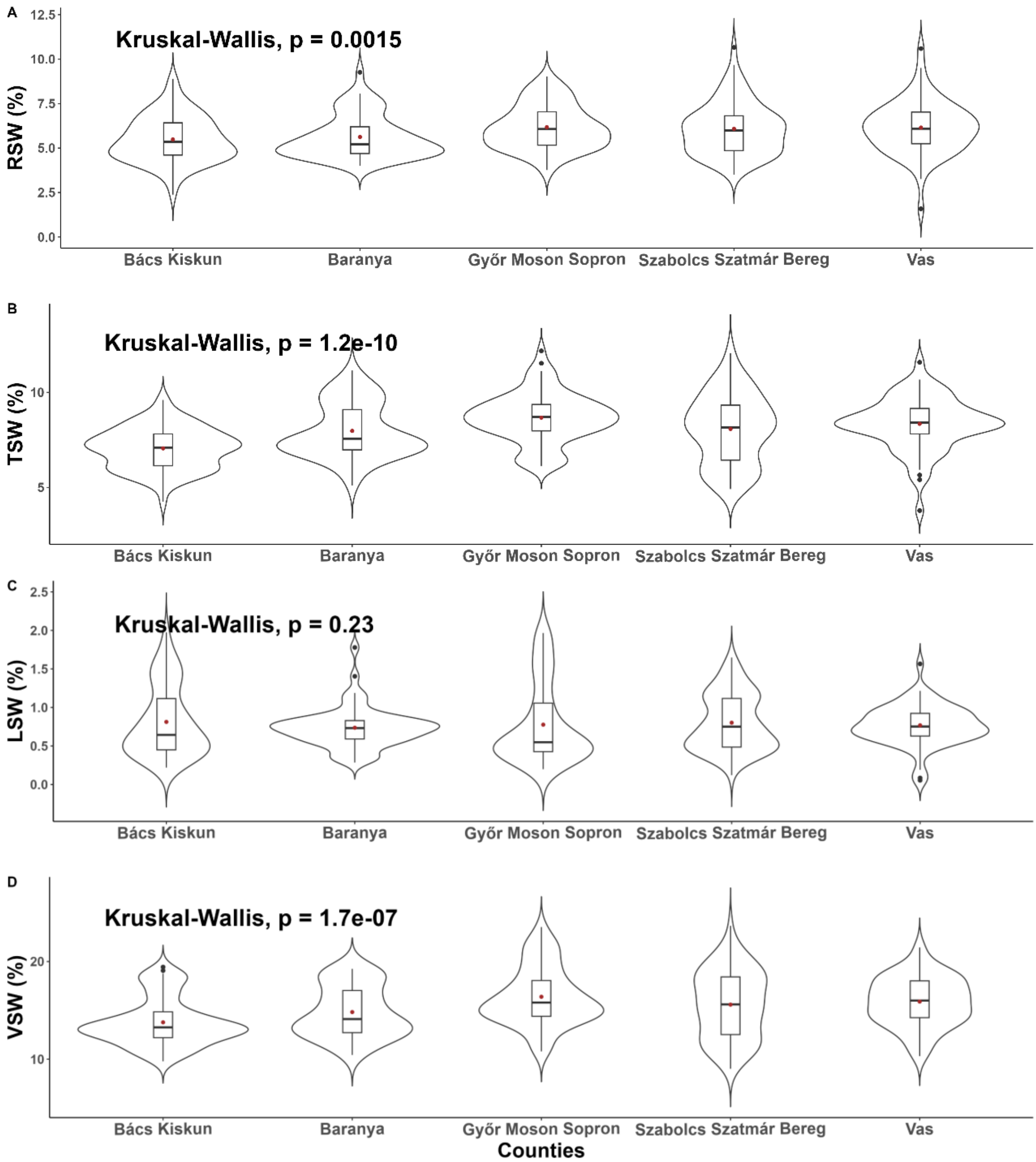


Figure 27: Data visualization of swelling for five counties. (A) radial swelling (RSW); (B) tangential swelling (TSW); (C) longitudinal swelling; (D) volumetric swelling (VSW)

3.3.6 Variability in the linear and volumetric shrinkage and swelling of Robinia wood among the growth conditions

Among the growth conditions, the wood samples from MPGC exhibited the highest dimensional and volumetric shrinkage and swelling, except for LSW as presented in Table 15. Statistical analysis (Kruskal-Wallis rank sum test) revealed significant differences in shrinkage among the growth conditions (Figure 28), with Kw squared = 21.551 for RSH and 19.591, 62.852 and 43.914 for TSH, LSH and VSH, respectively. In contrast, dimensional and volumetric swelling did not differ significantly (Figure 29). The Dunn test indicated no significant differences in shrinkage or swelling between GGC and PGC, whereas MPGC differed significantly from both other growth conditions as displayed in Table 15 also.

Site-specific factors significantly influenced ring width, as well as axial, tangential, volumetric, and radial shrinkage (Pollet et al., 2012). *Robinia pseudoacacia* L. regard as poor dimensional change. Across Hungary, the mean values for RSH, TSH, LSH and VSH were 4.54 %, 5.35 %, 0.8 % and 10.28 %, respectively. While that 5.91 %, 8.01 %, 0.78 % and 15.29 %, respectively, for RSW, TSW, LSW and VSW. Compared to values reported by Molnár and Bariska (2002) in Hungary, Pollet et al. (2012) in Belgium and Bijak and Lachowicz (2021) in Poland our finding showed lowest RSH, TSH and VSH. However, the LSH was higher than values of 0.1% and 0.3 % in Hungary and Poland, respectively, as shown in table 18 appendices. Additionally, Adamopoulos and Voulgaridis (2003) reported high values for radial and tangential shrinkage, at 5.30 % and 6.67%, respectively, and lower longitudinal shrinkage of 0.16 %. In term of swelling, our results show lower values of RSW, TSW, and VSW than those reported in the INCO Copernicus project "Technology for High Quality Products from Black Locust" (Babiak and Kurjatko, 2000).

Table 15: Basic statistic of shrinkage and swelling of wood *Robinia pseudoacacia* among the growth conditions

Growth conditions	No	Statistic	RSH %	TSH %	LSH %	VSH %	RSW %	TSW %	LSW %	VSW %
GGC	139	Mean	4.39	5.19	0.67	9.92	5.82	7.99	0.80	15.2
		Median	4.30 ^{a}	5.13 ^{a}	0.62 ^{a}	9.70 ^{a}	5.54 ^{ns}	7.79 ^{ns}	0.65 ^{ns}	14.3 ^{ns}
		Std	0.90	1.01	0.37	1.63	1.43	1.57	0.43	3.37
		Min	2.54	0.90	0.01	4.76	3.13	5.08	0.21	9.79
		Max	7.49	8.30	2.90	14.4	10.7	12.2	1.97	23.7
PGC	150	Mean	4.44	5.29	0.64	10.0	5.90	7.90	0.77	15.1
		Median	4.41 ^{a}	5.32 ^{a}	0.60 ^{a}	9.99 ^{a}	5.72 ^{ns}	7.89 ^{ns}	0.68 ^{ns}	15.0 ^{ns}
		Std	0.83	1.06	0.33	1.50	1.25	1.54	0.39	2.78
		Min	2.06	2.18	0.01	5.43	3.13	4.25	0.12	9.01
		Max	6.35	7.60	1.37	13.9	10.7	11.1	1.79	20.2
MPGC	58	Mean	5.12	5.93	1.62	11.9	6.15	8.35	0.76	15.9
		Median	4.99 ^{b}	5.83 ^{b}	1.22 ^{b}	11.4 ^{b}	6.09 ^{ns}	8.41 ^{ns}	0.75 ^{ns}	16.0 ^{ns}
		Std	1.04	1.17	0.09	2.00	1.49	1.39	0.26	2.51
		Min	2.99	2.03	0.19	6.54	1.58	3.78	0.05	10.3
		Max	7.58	8.57	3.89	15.9	10.6	11.6	1.57	21.4

***GGC= good growth conditions; PGC= poor growth conditions; MPGC= poor growth conditions (mixed species); RSH= radial shrinkage; TSH= tangential shrinkage; LSH= longitudinal shrinkage; VSH= volumetric shrinkage; RSW= radial swelling; TSW= tangential swelling; LSW= longitudinal swelling; VSW= volumetric swelling.

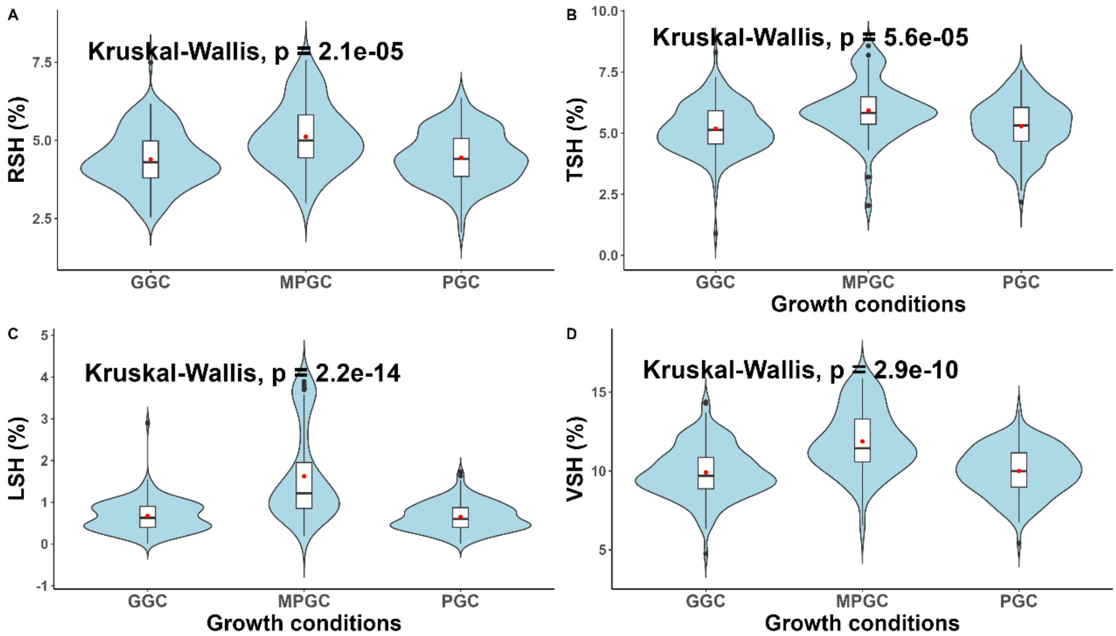


Figure 28: Data visualization of shrinkage mong growth conditions. (A) radial shrinkage (RSH); (B) tangential shrinkage (TSH); (C) longitudinal shrinkage; (D) volumetric shrinkage (VSH). GGC= good growth conditions; PGC= poor growth conditions; MPGC= poor growth condition mixed species.

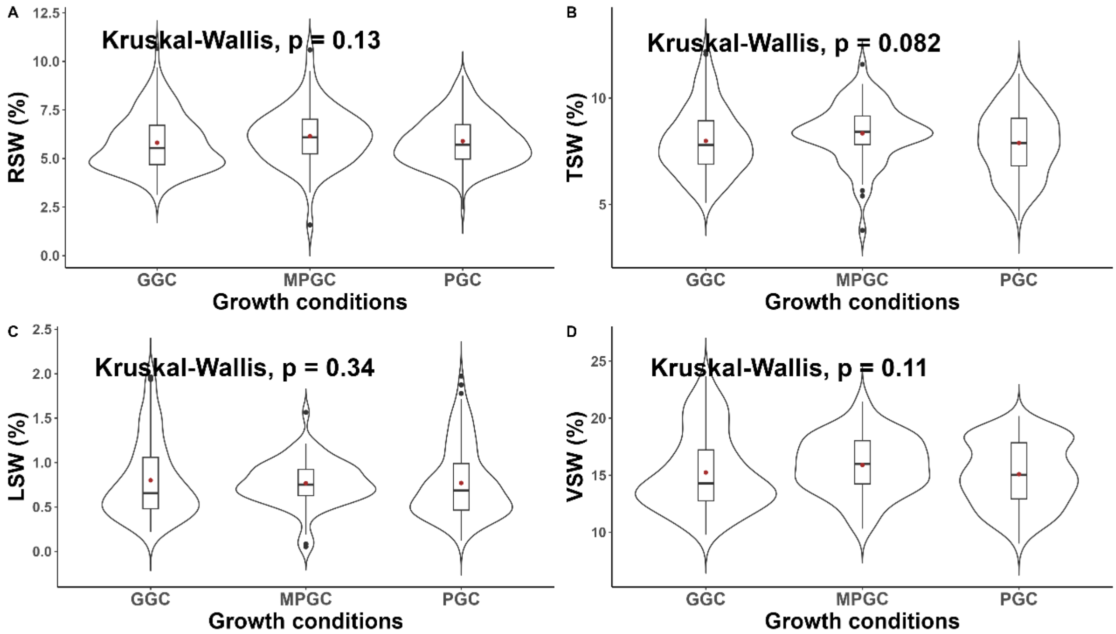


Figure 29: Data visualization of swelling among growth conditions. (A) radial swelling (RSW); (B) tangential swelling (TSW); (C) longitudinal swelling; (D) volumetric swelling (VSW). GGC= good growth conditions; PGC= poor growth conditions; MPGC= poor growth condition mixed species.

3.4 Mechanical properties of wood *Robinia pseudoacacia* L.

3.4.1 Modulus of elasticity (MOE) and modulus of rupture (MOR) across Hungarian counties

The mean, median, standard deviation (Std), minimum, and maximum values for MOE, MOR, and CS are presented in Table 16, along with their observed variability between counties. Across all counties, the overall mean values for MOE, MOR, and CS were 12,672 MPa, 125.52 MPa, and 66.95 MPa, respectively.

Among the individual counties, Bács Kiskun revealed the highest mean value for MOE, recorded at 13,335 MPa. Conversely, the highest MOR (146 MPa) and CS (73.4 MPa) were found in Győr-Moson Sopron County. The Kruskal-Wallis non-parametric test indicated substantial statistical variability in these mechanical parameters across the counties as shown in Figure 30. The resulting Kruskal-Wallis H-squared values were 16.309, 52.312, and 63.536 for MOE, MOR, and CS, respectively.

Table 16: Basic statistic of mechanical properties of wood *Robinia pseudoacacia* L.

County	No	Statistic	MOE (MPa)	MOR (MPa)	CS (MPa)
Szabolcs-Szatmár-Bereg	84	Mean	12,817	122	62.8
		Median	12,370 [a]	122 [a]	63.5 [b]
		Std	2,669	13.1	6.20
		Min	6,420	155	45.4
		Max	20,760	86.2	74.2
Bács Kiskun	61	Mean	13,335	112	68.6
		Median	12,740 [a]	115 [a]	69 [a]
		Std	3,184	20.7	8.26
		Min	7,140	68.1	49.1
		Max	23,810	156	85.1
Győr-Moson-Sopron	70	Mean	12,379	146	73.4
		Median	12,045 [ab]	144 [b]	71.6 [a]
		Std	2,362	28.6	11.1
		Min	8,050	86.4	50.8
		Max	19,250	203	100
Baranya	44	Mean	11,432	122	67.5
		Median	10,625 [b]	125 [a]	67.3 [a]
		Std	2,467	24.3	4.31
		Min	7,220	75.2	53.5
		Max	18,450	163	75.6
Vas	35	Mean	13,323	121	60.3
		Median	13,880 [a]	124 [a]	60.4 [b]
		Std	2,640	16.3	6.87
		Min	8,540	65.3	50.7
		Max	18,750	142	77.4
All		Mean	12,672	125.52	66.95
		Std	2,740	24.41	9.1

***MOE= Modulus of elasticity; MOR= Modulus of rupture; CS= Compressive strength

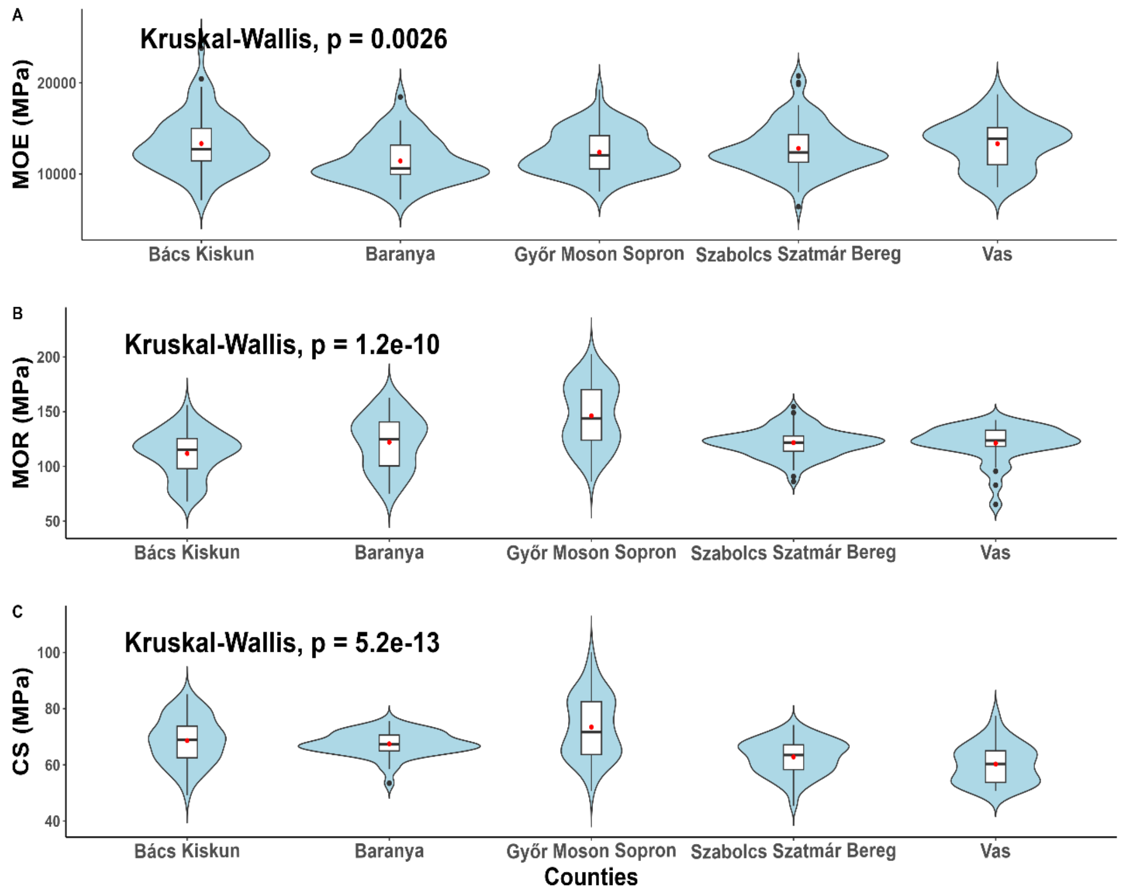


Figure 30: Data visualization and Kruskal-Wallis test of mechanical properties among counties. MOE= Modulus of elasticity; MOR= Modulus of rupture; CS= Compressive strength.

3.4.2 Mechanical properties variability among growth conditions

The MPGC demonstrated the highest mean values for MOE at 13,323 MPa. Likewise, the PGC showed the greatest MOR at 131 MPa, and CS at 71.9 MPa, (Table 17). Figure 31 shows significant variations in MOE (Kw squared = 11.298) and CS (Kw squared = 68.817) between the growth conditions. Conversely, the MOR was not significantly varied.

Black locust wood has been reported to exhibit moderate to high mechanical properties in Belgium, with mean values of 15.700 MPa for MOE and 138 MPa for MOR, which exceed those obtained for all counties in our study, and a lower CS of 63 MPa (Pollet et al. 2012). However, when compared with counties, only Győr Moson Sopron showed highest MOR, and all other counties revealed highest CS except Szabolcs Szatmár Bereg and Vas counties as well as the PGC–poor growth conditions. Moreover, earlier recaches in Hungary recorded almost similar MOE, MOR and CS (Molnár and Bariska, 2002; Nemeth et al. 2000). Recent study in Poland by Bijak and

Lachowicz (2021) recorded highest mean values for MOE 14,228.4 MPa, 155.5 for MOR and 75 MPa for CS. Compared with beech, Oak and Teak wood, Robinia pseudoacacia showed higher or similar physical and mechanical properties (Kamperidou et al. 2016; Pollet et al. 2012).

Table 17: Basic statistic of mechanical properties of wood *Robinia pseudoacacia* L.

Growth conditions	No	Statistic	MOE (MPa)	MOR (MPa)	CS (MPa)
GGC	130	Mean	13,059	122	63.9
		Median	12,450 [a]	124 [ns]	64.5 [a]
		Std	2,743	19.2	6.12
		Min	7,140	68.1	45.4
		Max	23,810	163	78.2
PGC	129	Mean	12,107	131	71.9
		Median	11,700 [b]	125 [ns]	70.7 [b]
		Std	2,677	29.6	9.60
		Min	6,420	75.2	51.2
		Max	20,760	203	100
MPGC	35	Mean	13,323	121	60.3
		Median	13,880 [a]	124 [ns]	60.5 [a]
		Std	2,640	16.3	6.87
		Min	8,540	65.3	45.4
		Max	18,750	142	77.4

***GGC= good growth conditions; PGC= poor growth conditions; MPGC= poor growth condition mixed species; MoE= Modulus of elasticity; MoR= Modulus of rupture; CS= Compressive strength.

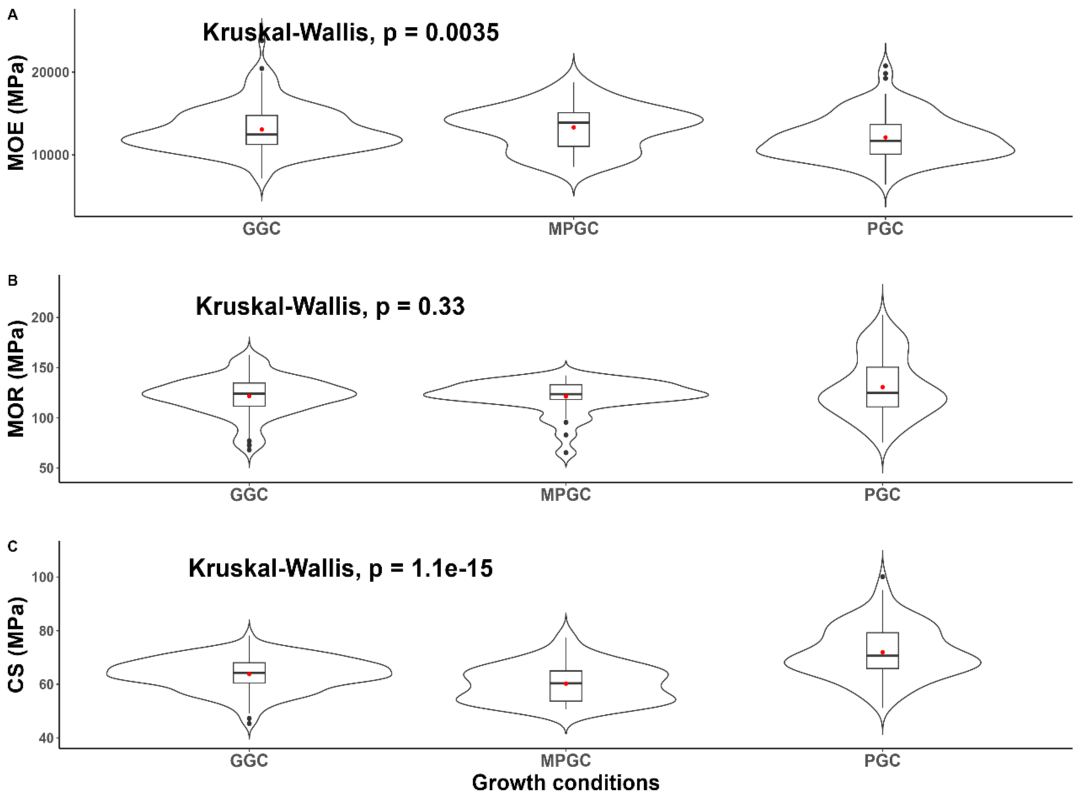


Figure 31: data visualization and Kruskal-Wallis of mechanical properties among growth conditions. MOE= Modulus of elasticity; MOR= Modulus of rupture; CS= Compressive strength.

3.4.3 Pearson's correlation between mechanical properties and basic density

BD weakly correlated with MOR (R = 0.23, p = 0.001), and CS (R = 0.35, p = 0.001), as seen in Figure 32. However, no correlation with MOE. The correlations between density and mechanical properties depend on wood species. This relationship can be affected by microfibril angel and slope of grain (Yang and Evans, 2003; Machado et al. 2014).

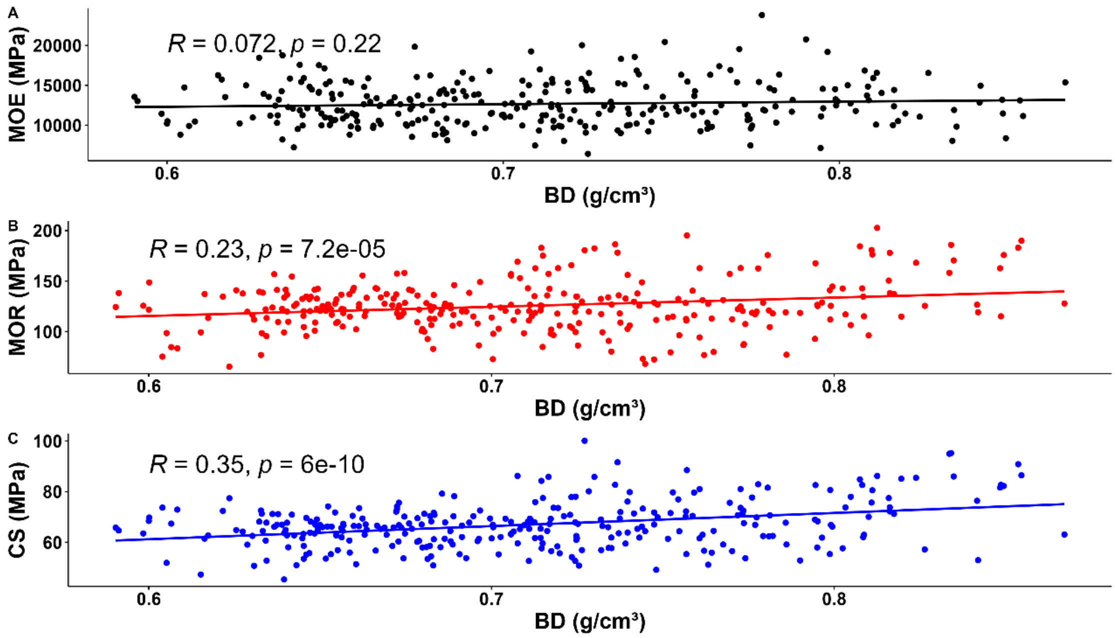


Figure 32: Correlation between basic density and mechanical properties. MOE= Modulus of elasticity; MOR= Modulus of rupture; CS= Compressive strength.

3.5 Principal Component Analysis (PCA)

Figure 33 displays the scree plot for the principal component analysis, in which PC1 accounts for the largest proportion of variance (49.4%). PC2 and PC3 explain an additional 19.6% and 16.5%, respectively. Subsequent components from PC4 to PC8 exhibit progressively smaller eigenvalues, with PC8 contributing negligible variance. The eigenvalues drop sharply from PC1 to PC2, followed by a more gradual reduction, forming a clear elbow and indicating that the explanatory value of components beyond PC3 is minimal.

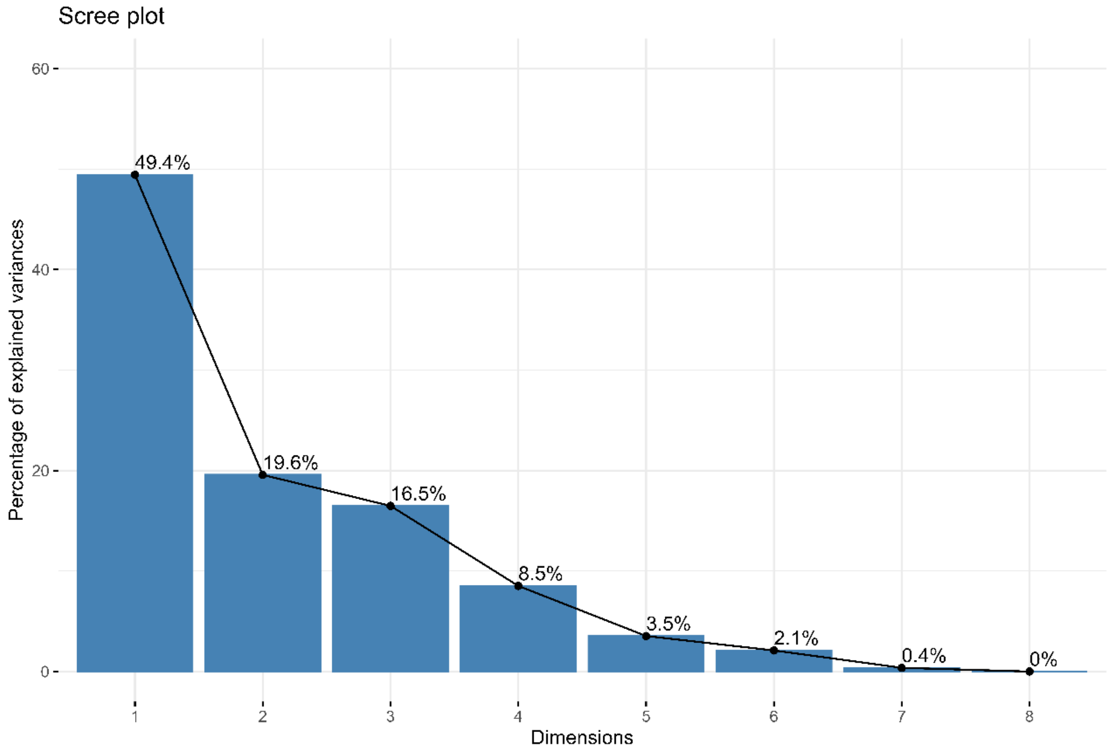


Figure 33: scree plot for the principal component analysis of variables contribution to the variation.

The PCA biplot in Figure 34 highlights the relationships between the Robinia wood properties and their origin sites across Hungary. The first two principal components (Dim1 and Dim2) captured 69% of the total variance, indicating an excellent representation of the underlying data structure. The loading plot shows that FW, FWT, TSH, VSH, L*, MWE, FRAP, TEC, and TPC have positive loadings on Dim1, whereas CYE, BD, and ADD exhibit negative loadings on Dim2. The strongest positive linear correlation (as indicated by vectors oriented in the same direction) was observed between TSH and VSH, while BD and ADD displayed the strongest negative correlations. Most of the properties contributing to PC1 were associated with samples from Vas County and MPGC, reflecting their higher measured values.

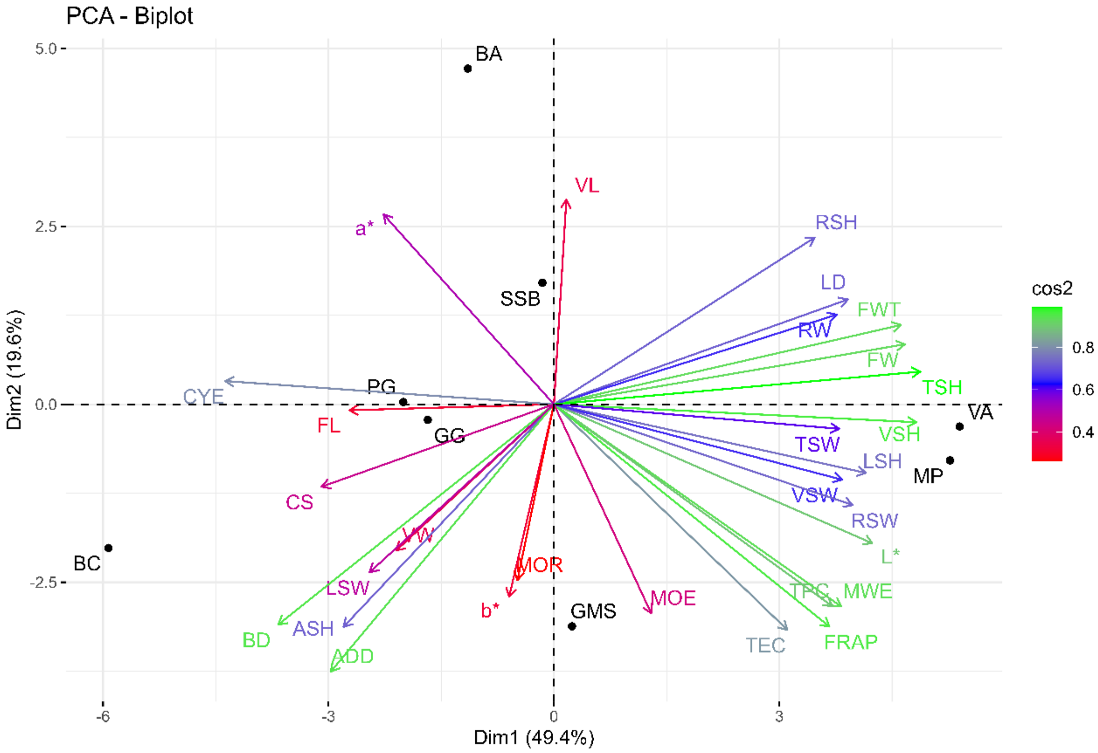


Figure 34: PCA loadings plot of the variables on the first two components. Vectors with green color showed strong correlations, blue showed moderate correlations and red showed no correlations. Black cercle in plot showed the counties and growth conditions. Counties, SSB= Szabolcs-Szatmár-Bereg; BC= Bács Kiskun; GMS= Győr-Moson-Sopron; BA= Baranya; VA= Vas; GG= good growth conditions, PG= poor growth conditions; MP= poor growth conditions mixed species.

4 CHAPTER FOUR

CONCLUSION AND RECOMNDATIONS

4.1 Conclusion

The following are some conclusions drawn from the literature review:

- The fundamental characteristics of wood *Robinia pseudoacacia* L. are significantly governed by site-specific environmental factors, soil composition, and tree age.
- Climatic variables, particularly air temperature and precipitation, substantially regulate annual ring width, while variations in light, water, and nutrient availability directly alter vessel width and density, thereby modifying overall wood growth patterns.
- Comparative analyses underscore these regional distinctions; for instance, black locust wood from Belgium exhibits higher tangential and volumetric shrinkage and a greater modulus of elasticity than samples collected from Poland and Hungary, whereas Hungarian wood showed larger latewood vessel diameters than those from Greece.

Based on the study findings the following conclusions can be drown:

Our research investigated the characteristics of wood *Robinia pseudoacacia* L., from wide distribution across Hungary.

- Across all counties and growth conditions, significant differences were observed in the investigated properties, with the exception of swelling, which did not vary significantly between the growth conditions. Szabolcs-Szatmár-Bereg and Vas counties, as well as the GGC–good Growth Conditions group, produced fibers with the most desirable characteristics and the widest ring widths.
- Vas and Győr Moson Sopron counties, in addition to MPGC–poor growth conditions mixed species exhibited the highest contents of extractives, phenol, and antioxidant capacity.
- All color parameters (lightness, redness and yellowness) showed significant correlation with CYE, while none were linked with TEC.
- Bács Kiskun recorded greatest ADD and BD, in reverse lowest linear and volumetric shrinkage and swelling. Additionally, the PGC–poor growth conditions showed highest values for both ADD and BD.

- Bács Kiskun County and MPGC revealed the maximum mean values for MOE, and the highest MOR and CS were found in Győr-Moson-Sopron and PGC.

The results clearly demonstrate that Robinia wood characteristics are significantly influenced by site-specific factors and growth conditions. We recommend that future research continue to address these aspects while also examining natural durability across different countries and environmental gradients. These findings are significant for optimizing wood applications and forest management in Hungary and provide a robust baseline for examining wood materials from other regions.

4.2 Limitation

- This study was limited by the fact that the wood material from Vas County, was collected from one location characterized by poor growth conditions and mixed species.

5 Summary

Robinia pseudoacacia L., is a species of substantial importance in Central Europe, particularly in Hungary, primarily due to its inherent drought tolerance. Given the pressures of ongoing climate change, this resilience positions *R. pseudoacacia* L., as a vital alternative species capable of satisfying rising industrial and consumer demand for durable timber. The wood of Robinia is highly valued because of its natural durability and superior resistance to decay and external environmental factors. The site conditions and soil types plays a crucial role regarding tree growth and then their wood quality by altering the wood anatomical properties and chemical compositions. This research investigated the characteristics of *R. pseudoacacia* L., wood from five Hungarian counties and three different growth conditions. The research focused on:

i- Anatomical features
ii- Chemical compositions.
iii- Physical properties.
iv- Mechanical properties.

Wood samples were collected from five counties in Hungary: Bács Kiskun, Szabolcs Szatmár Bereg, Vas, Baranya, and Győr Moson Sopron. These counties represent the East, middle, South and Southwest of Hungary. Within counties the wood sample was collected from different locations. The investigation of specific wood properties was conducted using standard methods and established International Organization for Standardization (ISO) protocols. The software (R (V4.3.2 (2023-10-31 ucrt) Core Team, RStudio, Inc., Boston, USA) was used to analyse the data.

The results of the anatomical properties assessment showed that Szabolcs-Szatmár-Bereg and Vas counties recorded fiber parameters with fiber lengths spanning from 1.04 to 1.11 mm. In line with this, the best fiber properties were noted in GGC, followed by MPGC.

The results regarding chemical extractives revealed that Vas County recorded the highest values for methanol-water extractives (11.8%), total extractives (13.4%), total polyphenol content (36.0 mg GAE/g dw), and antioxidant capacity (17.8 mg AA/g dw). In contrast, Baranya County showed the lowest levels of chemical extractives and the lowest lightness values. Among the growth conditions, the Mixed-species Poor

Growth Conditions (MPGC) group exhibited the highest lightness, whereas redness and yellowness were more intense in the Poor Growth Conditions (PGC) group.

The results of the physical properties analysis showed that Vas County and MPGC recorded the highest lightness. However, the PGC group showed the greatest redness and yellowness. Bács-Kiskun county and PGC revealed the highest ADD and BD. Also, Bács-Kiskun showed the lowest shrinkage and swelling.

The results of the mechanical properties showed that across all counties, the mean values for MOE, MOR, and CS were 12.672 MPa, 125.52 MPa, and 66.95 MPa, respectively. Among counties, Bács-Kiskun recorded the highest MOE with mean of 13.335.00 MPa, while Győr-Moson-Sopron documented the highest MOR at 146 MPa and CS of 73.4 MPa. The MPGC group showed the highest mean MOE with mean of 13.323.00 MPa, whereas the PGC group showed the highest MOR (131 MPa) and CS (71.9 MPa).

The relationships between maximum temperature/annual precipitation and fiber length or ring width indicated no significant correlations. However, correlation analysis revealed a significant positive relationship between lightness and methanol water extractives ($r = 0.55$) as well as total phenol content ($r = 0.48$). In contrast, lightness was negatively correlated with cyclohexane ethanol extractives. BD was weakly correlated with MOR and CS.

The principal component analysis shows that FW, FWT, TSH, VSH, L*, MWE, FRAP, TEC, and TPC have positive loadings on Dim1, whereas CYE, BD, and ADD exhibit negative loadings on Dim2. The strongest positive linear correlation was observed between TSH and VSH, while BD and ADD displayed the strongest negative correlations. Most of the properties were associated with samples from Vas County and MPGC, reflecting their higher measured values.

6 Novel findings

This study presents novel findings regarding the fundamental characteristics of *Robinia pseudoacacia* L. wood from five counties in Hungary, detailed as follows.

Thesis 1: anatomical feature of wood *Robinia pseudoacacia* L., across Hungary and among the growth conditions

I establish that the length, width, wall thickness of fiber and vessels length and width of wood *Robinia pseudoacacia* L. were greatest in Szabolcs-Szatmár-Bereg and Vas. Among the growth conditions, I found that in poor growth conditions (mixed species) and good growth conditions produced superior wood fiber properties and ring widths.

Thesis 2: Relationships of Fibers length and Ring Width with Precipitation and Temperature on Wood of *Robinia pseudoacacia*.

I proved that the fiber length, width, and cell wall of *Robinia pseudoacacia* L., from Bács Kiskun increased from pith to bark. While the lumen diameter remained without change. I found that the fiber length and ring width were not significantly correlated with precipitation and temperature.

Thesis 3: Chemical Compositions and Color Parameters of *Robinia pseudoacacia* L.) Wood across Hungary and among the growth conditions

I found that *Robinia pseudoacacia* L., from Vas and Győr-Moson-Sopron exhibited the highest total contents of extractives, polyphenol, antioxidant capacity and intense lightness. Under growth conditions, MPGC yield higher chemical composition. I also found that the extractives from the cyclohexane-ethanol solvent significantly correlated with all color parameters and conversely with total extractives content.

Thesis 4: densities, shrinkage and swelling of wood *Robinia pseudoacacia* L., across Hungary and among the growth conditions

I found that the air-dry and basic density of *Robinia pseudoacacia* L., were highest in Bács-Kiskun County and lowest shrinkage and swelling. I found that The PGC revealed greatest densities, and tangential and longitudinal shrinkage. While the MPGC recorded the greatest values for volumetric shrinkage, radial, tangential and longitudinal and volumetric swelling. I found that there were no significant differences in linear and volumetric swelling between the growth conditions.

Thesis 5: mechanical properties of wood *Robinia pseudoacacia* L., across Hungry and among the growth conditions

I found that the Bács-Kiskun has the highest mean values for MOE, while the highest MOR and CS were greatest in Győr Moson Sopron**.** I found that the MPGC demonstrated the highest MOE, whereas the MOR and CS were greatest in PGC.

I proved that the sites specific factors and growth conditions significantly affected the wood properties of *Robinia pseudoacacia* L., in Hungary. With highest studied properties in Vas County and MPGC.

Publications

journal articles

Younis, F.A.A.A., Báder, M., Bak, M. and Németh, R., 2025. Site Variability in Fibers, Vessels, and Ring Width of *Robinia pseudoacacia* L. Wood: A Case Study in Hungary. Forests, 16(5), p.807. **Thesis.**

Younis, F.A.A.A., Báder, M., Bak, M. and Németh, R., 2024. Relationships of Fibers length and Ring Width with Precipitation and Temperature on Wood of *Robinia pseudoacacia*. (Book chapter, Sopron University). **Thesis.**

Younis, F.A.A.A., Govina, J.K., Seidu, H. and Németh, R., 2023. Basic Characteristics of Black Locust (*Robinia pseudoacacia* L.) Wood Grown Under Different Site Conditions: A Review. ACTA SILVATICA ET LIGNARIA HUNGARICA: AN INTERNATIONAL JOURNAL IN FOREST, WOOD AND ENVIRONMENTAL SCIENCES, 19(1), pp.21-35. **Thesis.**

Younis, F.A.A.A. and Németh, R., 2023. Variation in Moisture Content and Density Whitin and Among Freshly Felled *Sclerocarya birrea* and *Anogeissus leiocarpus*. BULLETIN OF THE TRANSILVANIA UNIVERSITY OF BRASOV SERIES II-FORESTRY, WOOD INDUSTRY, AGRICULTURAL FOOD ENGINEERING, 16(3), pp.227-234.

Younis, F.A.A.A., Abdelgadir, A.Y., Ahmed, Z.A., Govina, J.K. and Németh, R., 2022. Inter-and intraspecific differences in physical and mechanical properties of wood from *Sclerocarya birrea* and *Anogeissus leiocarpus*. Acta Silvatica Et Lignaria Hungarica: An International Journal in Forest, Wood and Environmental Sciences, 18(1), pp.57-69.

Younis, F.A.A. and Yasin, E.H., 2025. The Characteristics of Popular Hardwood Species in Sudan-Review. Forest Science – Advances Towards Sustainable Development and Climate Resilience. (Book chapter, IntechOpen).

Seidu, H., Németh, R., Owusu, F.W., Korang, J., Appiah-Kubi, E., Govina, J.K. and Younis, F.A.A.A., 2023. Mechanical properties of PF and MUF bonded juvenile hybrid eucalyptus plywoods produced in Ghana. Wood Research, 68(3), pp.521-531. (Q2).

Conference publications

Younis Fath Alrhman, Báder Mátyás, Németh Róbert, 2025. Плотность древесины и механические свойства древесины Robinia pseudoacacia L. из трех регионов Венгрии. In: Gordin MV (eds.). Русский инженер (Russkii inzhener). Conference: Москва, Russia 2025.10.29. - 2025.10.31. Москва: Bauman Moscow State Technical University, pp 14-15 (2025). Language: Russian | Book link(s): ISBN: 9785703866566.

Younis, F.A.A.A. and Németh, R., 2025. Comparative Study of Fiber Characteristics in Mature and Juvenile *Robinia pseudoacacia* L. Heartwood. Book of Abstracts of 8th International Conference on Process Technologies for the Forest and Biobased Products Industries 2025. Conference: Kuchl, Austria 2025.09.18. - 2025.09.19. Salzburg University of Applied Sciences Design and Green Engineering Department Campus Kuchl, pp 20-20 (2025).

Younis, F.A.A.A., Németh, R. and Báder, M., 2024. Compensatory Anatomical Studies on Robinia, Sclerocarya and Ulmus. In: Németh, Róbert; Hansmann, Christian; Militz, Holger; Bak, Miklós; Báder, Mátyás (eds.) 11TH HARDWOOD CONFERENCE PROCEEDINGS: Sopron, Hungary, 30-31 May 2024. 10. 14.

Younis, F.A.A.A. and Németh, R., 2023. Variation in Moisture Content and Density Whitin and Among Freshly Felled *Sclerocarya birrea* and *Anogeissus leiocarpus*. BULLETIN OF THE TRANSILVANIA UNIVERSITY OF BRASOV SERIES II-FORESTRY, WOOD INDUSTRY, AGRICULTURAL FOOD ENGINEERING, 16(3), pp.227-234.

Younis, F.A.A. and Németh, R., 2022. Extractives content of wood *Sclerocarya birrea* and *Anogeissus leiocarpus* trees. In: Róbert Németh (Németh Róbert Faanyagtudományok) SOE/FWECI/Institute of Wood Engineering; Christian Hansmann; Peter Rademacher (Rademacher Peter Erdészet, faipar) University of Sopron; Miklós Bak (Bak Miklós Faanyagtudomány) SOE/FWECI/Institute of Wood Engineering; Mátyás Báder (Báder Mátyás Faanyagtudomány) SOE/FWECI/Institute of Wood Engineering (eds.) 10TH HARDWOOD CONFERENCE PROCEEDINGS.

Appendices

Table 18 A1: Literature-derived values for the average physical properties of wood *R. pseudoacacia* L. Hungary (Molnár and Bariska, 2002); Belgium (Pollet et al. 2012); Poland (Bijak and Lachowicz, 2021).

Characteristics	Hungary	Belgium	Poland
Fresh felled moisture content (%)	35–45		
Fiber saturation point (%)	21.8–22.5		
Oven dry density (kg/m^3)	540–740-870	529–857	
Air dry density (kg/m^3)	580–770-870		
Green density (kg/m^3)	800–900-950		
Longitudinal shrinkage (%)	0.1		0.3
Tangential shrinkage (%)	5.4–7.2	8.8	6.8
Radial shrinkage (%)	3.2–4.6	5.5	5.1
Volumetric shrinkage (%)	11.4–12.2	16	11.7
Porosity (%)	52		52.7
Thermal properties Bark-free wood (KJ/Kg)	17,777		
Bark (KJ/Kg)	19,145		
Bole (in bark) (KJ/Kg)	18,047		
Thick roots (KJ/Kg)	17,223		

Table 19 A2: Literature-derived mean values for mechanical characteristics of wood *R. pseudoacacia* L. CS = compression strength; JW = juvenile wood; MW = mature wood; MOE = bending modulus of elasticity; IBS = Impact bending strength. Hungary [a] (Molnár and Bariska 2002); Hungary [b] (Nemeth et al. 2000); Hungary [c] (Kamperidou et al. 2016); Poland (Bijak and Lachowicz 2021); Belgium (Pollet et al. 2012); Greece (Adamopoulos, 2007).

Characteristics	Hungary [a] (MPa)	Hungary [b] (MPa)	Hungary [c] (MPa)	Poland (MPa)	Belgium (MPa)	Greece (MPa)
Tree age (years)					61–100	21–37
Mean axial CS					63.3	
Longitudinally CS	62-72-81			75		
Across the grain CS	18.5					
Axial CS in JW						61.57–65.56
Axial CS in MW						64.48–71.02
Tensile strength	166.8					
Bending strength (MOR)	103-136-169	152	173.02	155.5	138	
Bending strength in JW						28.30–153.5
Bending strength in MW						142.8–156.7
Share strength	11-13-16					
Radial cleavage	1.12					
Tangential cleavage	0.6–1.1					
Average hardness					5.22	
End hardness	67-78-88					
Side hardness	28					
Radial hardness			8.09			
Tangential hardness			7.48			
Mean MOE	9,000- 11,300-13,000	12,631-13,384	18,122	14,228	15,700	
MOE in JW						13,507–15,416
MOE in MW						14,437–15,256
IBS	12-14-18 J/cm^2		3.37 N/mm^2		17.21 J/cm^2	

Table 20 A3: Values of anatomical features of *R. pseudoacacia* L. wood derived from the literature. VT= vessel tissue; FL= Fiber length; VD= vessel diameter; VL= vessel length; EW= early wood; LW=late wood; GM= general mean; WEV= Wide earlywood vessel; RW= ring width. Sources: Hungary (Molnár and Bariska 2002); Greece [b] (Adamopoulos and Voulgaridis 2002); Belgium (Pollet et al. 2012)

Literature	Libriform fiber (%)	VT (%)	Rays (%)	FL (mm)			VD (µm)		VL (mm)		WEV (µm)	RW (mm)
				GM	EW	LW	EW	LW	EW	LW		
Hungary	58	15	21	1				70–140			150–220	
Greece [b]					0.77	1.04	47	24	0.16	0.18		3.4
Belgium												2.9

Table 21 A4: Mean values of *R. pseudoacacia* chemical properties (%) derived from the literature. SW= sapwood; HW= heartwood; JW= juvenile wood; MW= mature wood. Sources: Hungary (Molnár and Bariska 2002); Hungary [c] (Passialis et al. 2008); Bulgaria (Passialis et al. 2008); Bulgaria b (Panayotov et al. 2015); Greece c (Passialis et al. 2008); Greece d (Adamopoulos et al. 2005); Czech Republic (Sablík et al. 2016).

Property	Hungary	Hungary [c]	Bulgaria	Bulgaria [b]	Greece [c]	Greece [d]	Czech Republic
Elementary composition in the xylem							
C	49.2						
H	5.91						
O + N	43.1						
Ash (general mean)	0.79			0.32–0.61			
ash in the bark	4.76	7.24–8.56	8.54		8.37		
ash in the SW	0.98	0.72–1.24	1.24		1.13	0.65–0.76	
ash in the HW	0.26	0.34–0.89	0.71-0.89		0.47–0.46	0.36–0.76	
Cellulose	40–50			45.4–49.0			
Hemicellulose	15–22						
Lignin (mean)	25–30			23.0–27.7			
lignin in HW						18.33–25.73	
lignin in SW						18.13–21.42	
Tannin in the bark	3–6						
Tannin in the xylem	2–4						
Hot water extractive contents							
JW		5.15–9.53	6.94-		5.04–8.71	8.7–9.8	
MW			10.10			4.7–5.5	
SW		3.33–4.16			6.76		
bark		9.25–12.31	4.36		13.49		
			13.14				
Dichloromethane extractive contents							
JW		0.53–0.90	0.57–0.71		0.76	0.9–1	
MW							
SW		0.48–1.05	1.47		1.32	1.1–1.9	
bark		3.95–4.03	3.09		3.62		
Methanol:water (1:1, v/v) extractive contents							7.41
HW							9.56
bark							

Table 22 A5: Literature-derived inorganic components of *R. pseudoacacia* wood and bark in ppm1. JW= juvenile wood; MW= mature wood; SW= sapwood; B= bark; HW= heartwood; Mn=Manganese; Fe= Iron; Cu= Copper; Zn= Zinc; Pb= Lead. Sources: Hungary and Bulgaria (Passialis et al. 2008); Greece (Adamopoulos et al. 2005)

previous studies	position	Ca	K	Mg	Na	P	Mn	Fe	Cu	Zn	Pb
Hungary (Clone NY)	JW	1,710	281	112	43	21	0.7	13	4.1	13	15
	MW	821	243	62	39	13	0.6	20	2.6	8.4	15
	SW	1,210	1,486	192	64	122	1.4	8.6	3.8	14	14
	B	20,967	2,592	303	466	119	7.0	59	7.9	29	35
Bulgaria	JW	1,658	965	168	69	15	1.8	14.4	3.1	16	24
	MW	2,462	1,046	173	68	19	1.5	10	2.7	17	12
	SW	2,371	2,634	349	70	151	3.3	15	4.4	21	23
	B	27,406	3,505	526	414	239	33	116	9.2	48	38
Greece	*Bottom*										
	HW	1,615	95	180	118	9	1	30	5	6	0.134
	SW	1,478	1,250	305	168	222	2	32	5	7	0.340
	Middle										
	HW	1,830	383	163	187	21	2	23	5	5	0.268
	SW	2,027	1,067	187	190	206	21	1	5	5	0.550
	Top										
	HW	2,013	650	158	113	35	2	21	4	4	0.088
	SW	183	1,845	617	182	198	27	2	5	6	0.257

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