DOCTORAL (PHD) DISSERTATION

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Head of School: Professor Dr. Laszlo Bejo

COMPARATIVE STUDY OF WOOD PROPERTIES FOR *QUERCUS CERRIS* L. (TURKEY OAK) FROM DIFFERENT SITES IN HUNGARY.

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Sopron, Hungary

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COMPARATIVE STUDY OF WOOD PROPERTIES FOR *QUERCUS CERRIS* L. (TURKEY OAK) FROM DIFFERENT SITES IN HUNGARY.

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Abstract

Floral ecophysiologists and foresters in Europe and Hungary have classified *Quercus cerris* L. (Turkey oak), a temperate hardwood species, as a drought-tolerant tree species. In Hungary, the species is a lesser-used timber material. This research investigated the effects of soil quality and stand composition on wood tissues of Turkey oak in Hungary. Four trees were randomly harvested from each of the five selected Counties in Hungary. Further in Vas County only were plots under the influence of soil quality and stand composition, where four trees were randomly harvested from each. Logs processing, wood samples preparation and testing were performed at the Natural Resources Research Centre of the University Sopron (Soproni Egyetem, Hungary).

Wood materials from Vas had the highest mean heartwood proportions of 75% followed by materials from Baranya with 71%. The combination of soil quality and stand composition had a slight statistically significant effect on the heartwood-sapwood proportion. The mean annual tree-ring width (TRW) for the wood materials ranged from 1.32 to 3.68 (mm). The Juvenile portion of materials from Baranya recorded the widest mean TRW (3.68 mm). Overall, the TRWs for Turkey oak trees planted in mixed stands were larger than trees from pure species stands. Similarly, the early- and latewood widths recorded were larger for Turkey oak trees from mixed species stands. There was a weak to moderate positive correlation between precipitation and TRW. The correlation between maximum temperature and TRW was negative.

The mean values of fibre length (FL) ranged from 1065.14 to 1529.27 (μm). The highest mean FL of 1529.27 was recorded for sapwood portion of materials from Komárom-Esztergom. Wood materials from the Gyor-Moson-Sopron (GMS) recorded the lowest FL. The mean values of fibre double wall thickness (FDWT) ranged from 12.94 to 15.13 (μm). The minimum mean value was from GMS heartwood materials whereas the maximum value was from the sapwood of trees from Vas. Considering soil quality plots within the Vas County, the mean values for FL of wood from good and poor soil were 1096.69±291 μm and 1179.59±201 μm, respectively. FDWT were 13.7±5.24 μm and 16.67±4.98 μm, respectively. Regarding stand composition plots within Vas Country, FL for wood from mixed- and pure-stands were 1273.6±192 μm and 975.89±223 μm, whereas its corresponding FDWT 17.29±5

μm and 12.92±4 μm, respectively. The results indicate that Turkey oak wood from mixed stands, irrespective of soil quality, produced wood with longer fibres and thicker walls.

On good quality soil, the average vessel diameter was 111.44±38 μm, whereas on poor quality soil the average was 236.87±140 μm. Vessel length was similar in both earlywood and latewood portions, their diameters were expectedly larger in the earlywood portion. The proportion of vessels was greater in wood from pure stands. The mean values for vessel proportion ranged from 40 – 44%, and that of fibre 39 – 43%. Counterparts from mixed-species stands expressed mean vessel proportion ranging from 32 – 34%, and fibre from 44 – 47%.

Basic wood density values ranged from 0.65 to 0.87 g/cm^3. The wood materials from mixed-species exhibited higher basic density. The bending modulus of elasticity (MoE) ranged from 8929.74 to 15954.08 (MPa). Higher mean values were recorded for wood materials from mixed-species stands. The bending strength ranged from 104.04 to 167.89 (MPa). The compression strength parallel to the grain ranged from 49.55 to 70.08 MPa. Stand composition and soil quality had significant influence on basic density, MoE and MoR. Janka hardness$_{_longitudinal}$ ranged between 77.15 to 106.71 N/mm^2. The same variable tested on radial surface ranged between 63.22 to 88.26 N/mm^2 whereas on tangential surface ranged between 64.43 to 93.10 N/mm^2. Turkey oak wood materials from mixed-species planting exhibited better mechanical properties apart from compression strength. Hungarian Turkey oak is recommended for valuable applications such as floorings, furniture and cabinets and lasting structural constructions.

Absztrakt

Az európai és magyarországi ökofiziológusok és erdészek a mérsékelt égövi lomos *Quercus cerris* L. fafajt (csertölgy) a szárazságtűrő fafajok közé sorolták. A csertölgy Magyarországon jelenleg alul használt fafaj, annak ellenére, hogy részben a nemes tölgyekhez hasonló tulajdonságokat mutat. Kutatásomban a termőhely és az állományösszetétel hatását vizsgáltam a magyarországi csertölgy faanyagának szöveti szerkezetére. Magyarország öt kiválasztott megyéjéből véletlenszerűen négy-négy fát termeltünk ki. Vas megyében a mintaterületeket a talajminőség és az állományösszetétel függvényében választottuk ki. Ezekről a speciális területekről is négy-négy fát vágtunk ki véletlenszerűen. A faanyag feldolgozása, a vizsgálatra szánt faanyagminták kialakítása a nemzetközi szabványokat követték. A kutatást a Soproni Egyetem faipari műhelyeiben és laboratóriumaiban végeztem el. A geszt sötétebb barna volt, mint a szijács.

A Vas megyéből származó faanyagoknál volt a legmagasabb a geszt aránya, átlagosan 75%, amelyet a Mecsek területéről származó anyagok követtek 71%-kal. A termőhely és az állomány összetétele együttes hatása statisztikailag szignifikáns hatással volt a szijács-geszt arányra. A faanyagok átlagos évgyűrűszélessége 1,32 és 3,68 (mm) között mozgott. A Mecsek anyagainak juvenilis része mutatta a legszélesebb átlagos évgyűrűszélességet (3,68 mm). Összességében az elegyesen ültetett csertölgyek évgyűrűszélessége nagyobb volt, mint az elegyetlen állományokban nőtt fáké. Hasonlóképpen, a korai és a késői pászta szélessége is nagyobb volt az elegyes állományokból származó fáknál (elegyetlenhez képest). A csapadék és az évgyűrűszélesség között gyenge vagy mérsékelt pozitív korreláció volt kimutatható. Ezzel szemben a maximális hőmérséklet igazioltan negatívan befolyásolta a vastagsági növekedést.

A rosthossz átlagértékei 1065,14 és 1529,27 (μm) között mozogtak. A legmagasabb, 1529,27 μm-es értéket a szijács faanyagokban mutattam ki. A soproni területről származó faanyagok esetén volt a legalacsonyabb a rosthossz. A farostok kettős falvastagságának átlagértékei 12,94 és 15,13 (μm) között mozogtak. A legkisebb átlagértéket a gesztfa anyagokból, míg a legnagyobb értéket a fák szijács faanyagából kaptam. Kizárólag a talajminőséget figyelembe véve a jó és gyenge talajon nőtt faanyagok rosthosszának átlagértéke 1096,69±291 μm és 1179,59±201 μm volt. A farostok kettős falvastagsága

13,7±5,24 μm és 16,67±4,98 μm volt. Az elegyes és elegyetlen állományokból származó faanyag rosthossza 1273,6±192 μm és 975,89±223, míg a kettős falvastagság 17,29±5 μm és 12,92±4 μm volt. Az eredmények azt mutatják, hogy az elegyes állományokból származó csertölgy a talaj minőségétől függetlenül hosszabb rostú és vastagabb sejtfalú faanyagot eredményezett.

A jó minőségű talajon az átlagos edényátmérő 111,44±38 μm volt, míg a rossz minőségű talajon 236,87±140 μm. Az edénytagok hossza hasonló volt a korai és a késői pásztákban, az átmérőjük a korai pásztában (várhatóan) nagyobb volt. Az edények területaránya nagyobb volt az elegyetlen állományokból származó faanyagban. Az edények területarányának átlagértékei 40-44% között mozogtak, a farostoké pedig 39-43% között. Az elegyes állományokból származó társaik átlagos edényaránya 32-34%, a farostoké pedig 44-47% között mozgott.

A faanyag bázissűrűsége 0,65 és 0,87 g/cm^3 közötti volt. Az elegyes állományokból származó faanyagok nagyobb bázissűrűséget mutattak. A hajlító rugalmassági modulus (MoE) 8929,74 és 15954,08 (MPa) között változott. Az elegyes állományokból származó faanyagok esetében magasabb átlagértékeket állapítottam meg. A hajlítószilárdság 104,04 és 167,89 (MPa) között mozgott. A rostokkal párhuzamos nyomószilárdság 49,55 és 70,08 MPa közötti értékeket vett fel. A Janka keménység hosszirányban 77,15 és 106,71 N/mm^2 között mozgott; a Janka keménység sugár irányban 63,22 és 88,26 N/mm^2 között változott, a Janka keménység tangenciális irányban 64,43 és 93,10 N/mm^2 között mozgott. Az elegyes állományokból származó csertölgy faanyagok jobb mechanikai tulajdonságokkal rendelkeztek.

Chapter 1. General introduction

1.1 Introduction

Environmental research experts have predicted that there will be a warmer and dryer climate across the globe in the years ahead. The predicted climate will affect necessary growth factors such as soil moisture and organic matter breakdown. While some trees may react by slowing down their growth and biomass productions, other trees will have their survivorship threatened. This will also have a rippling effect on trees species diversity among stands. The tree species that have the natural tendency to survive are those termed as drought-tolerant. They provide for the future supply of biomass to related industries. Inarguably, Foresters or tree growers would prefer among other traits, plantlets that are drought-tolerant and fast-growing. Efforts to reach this overall achievement would be easier when naturally occurring drought-tolerant species are prioritised as important.

In Europe, notable drought-tolerant timber species include Turkey oak (Illés & Móricz, 2022; Móricz et al., 2021). Turkey oak species have been cultivated in forest stands across Hungary. It is the fourth most important wood species in terms of area and standing volume. According to a national report, in 2015, a total volume of 815 thousand m^3 of Turkey oak was felled (Nemzeti Élelmiszerlánc-biztonsági Hivatal, Erdészeti Igazgatóság, Budapest, 2016). However, the wood for Turkey oak is industrially under-utilized in this territory, though it's a hard and robust hardwood. A notable valued added application for Turkey oak wood is flooring. Other value-added applications and efficient promotion of the wood from Turkey oak will rely on the availability of extensive knowledge of its wood properties. There should be scientific information that investigated the variability of Turkey oak wood with regards to growth conditions within Hungary.

The growth factors in every forest matter because of the potential variation in the quality of conditions across larger coverage. The influence of soil quality on wood properties has been extensively studied (Zobel & van Buijtenen, 1989). Particularly, for the genus Quercus, evidence of site influence on tree growth and wood formation has been established (Nazari et al., 2020; Sousa et al., 2018; Guilley et al., 2004). Similarly for other hardwood species such as Hornbeam, site factors like altitude were found as a source of variation in some studies (Kiaei, 2013; Samariha, 2011). Kiaei and Abadian (2018) also found differences in wood properties after comparing materials from dominant and shaded trees. Unfortunately for Hungary where there are important and spatially distributed standing volumes of Turkey oak trees, research with such focus is limited. Therefore, a comparative study of the wood properties of Turkey oak under the current climate conditions is necessary. Especially now and in the future, since the call for valuable utilization of underutilized wood species in Hungary is on the ascendancy.

1.2 Hypothesis

Wood is a renewable, green, environmentally friendly material. It has superb and versatile working properties that are usually presented in varied quality ranges per species. For instance, different wood materials have varied colour shades; the strength properties range from soft and lightweight to hard and very heavyweight; natural wood durability is ranked to be degraded in weeks to hundreds of years. The versatility and variability of wood materials make them suitable for diverse applications. Unfortunately, most wood properties are dimensionally unstable, influenced by its moisture sorption (water absorption and desorption) and anisotropy behaviour. Regarding sensitive engineering applications, the dimensional instability in the strength properties of wood is a major processing and utilization impediment (Walker, 1993). In effect, civil engineers do not prefer wood in strength-sensitive applications.

The variability in wood quality for wood species is attributed to numerous factors. The factors in their singular or combined capacity affect the wood formation at cellular and microscopic levels. The study was therefore conducted with the following hypothesis:

1. Mixed-species stand of Turkey oak will produce wood of similar properties as counterparts from pure stand.
2. If Turkey oak is planted on soils with distinct quality, then their wood properties will differ to compromise wood quality.

The development of woody tissue cells (fibres, vessels, parenchyma) in Turkey oak will be affected if they are grown in plantations of non-uniform stand composition. For instance, in the scenario of mixed-species stand (Turkey oak grown among other hardwood species), the morphological structure of the various tree species could affect their physiological processes. Such a silvicultural set-up, among other factors like climate, would eventually contribute to the wood formation in the various species. The crown and root structures of different tree species vary, and this is reflected in their functions of photosynthesis and moisture absorption respectively. It is already established that the natural properties of wood (physical, strength, and other technological properties such as wettability) are influenced by its anatomical properties. This includes the positive relationship between fibre length and wall thickness to wood basic density and by extension to other strength properties.

Meanwhile, the within-stand variation in wood tissue characteristics is expected to be higher in trees grown in pure stands. This suggests that the wood quality will be compromised by silvicultural practices. In literature, mixed stands have been recommended to provide enhanced wood quality, forest health and ecosystem vitality. Similar to the arguments mentioned above on species composition, wood tissue development and wood formation in Turkey oak trees on Hungarian poor-quality soil is expected to differ at its anatomical level. The existing knowledge that some anatomical traits correlate with mechanical properties of wood suggest that Turkey oak will not be an exception. A significant deviation in anatomical properties will affect mechanical properties.

1.3 Research aim and objectives

Aim:

Macroscopic and microscopic characterization variability, as well as mechanical properties in Turkey oak wood as induced by different site conditions and silviculture to promote their efficient and valuable utilization.

Objectives:

1. To determine the proportion of heartwood and sapwood.
2. To determine annual tree-ring characteristics.
3. To determine the relationship between the annual tree-ring and climate variable (precipitation and temperature).
4. To determine the dimensions of fibre and vessels.
5. To determine the proportion of fibre, vessels and parenchyma per 1 mm^2 area for the wood Turkey oak.
6. To determine basic wood density.

7. To determine the bending and compression strength, bending modulus of elasticity, and Janka hardness.

1.4 Justification

Every ecosystem thrives on a particular set of environmental conditions to function (Ali, 2023; Wallis et al., 2021). The forecasted rise in atmospheric temperatures and its associated droughts will affect forest ecosystems. Tree species are resilient and can adapt to a certain limit, yet beyond this limit, many tree species will be threatened. In severe cases, some tree species will be threatened in the new ecosystem under the occurring warming temperature conditions. On the other hand, the growth of tree species that survive any extreme warm conditions can be altered. The evidence of tree growth alterations is registered in its wood formation. Daily maximum temperature and precipitation are the main regulators of cambial activity towards wood formation (Cabon et al., 2020).

Potentially, there will be a shift in species compositions as observed for some oak species in the west of Hungary (Axer et al., 2021; Mészáros et al., 2022). Illés & Móricz (2022) suggested that the land coverage for Central European species has been significantly rearranged. This might depict climate change mitigation, in terms of carbon sequestration. There can be some tree species that will survive, but their growth rates of productivity may be reduced in the future. The under-performance of ecosystems could make climate change mitigation more challenging. A slower tree growth rate also suggests that there is reduced woody biomass per year. The wood industry will continue to be at a disadvantage because of the likely raw material shortage. In addition, the wood quality of the raw wood formed under adverse conditions cannot be guaranteed.

Chapter 2. Literature review

2.1 Wood formation and its relevance

The formation of secondary xylem (wood) in trees is a complex and irreversible biological process of expansive and structural development (Hilty et al., 2021). Wood formation is a fundamental process that trees undergo to produce and differentiate new xylem cells that finally mature into functional wood cells (Fromm, 2013; Plomion, 2001). The developmental process, technically termed xylogenesis, is the same in both angiosperm and gymnosperm. Vascular cambium, which is derived from the procambium, is a single layer meristematic tissue responsible for the initiation of wood formation (Hartmann et al., 2017). Secondary growth at the roots and shoots is the result of functional vascular cambium (Larson, 1994). The vascular cambium is comprised of cell initials that produce xylem cells to the inner part of the tree trunk whereas phloem cells are produced towards the outer (Figure 1) (Pallardy, 2007).

The wood formation process involves two divisional strategies by the vascular cambium. There is periclinal division by elongated fusiform initials that produce individuals into the axial cell system in every wood (tracheary elements, i.e. tracheids in softwoods and vessel elements in hardwoods, fibres and axial parenchyma cells), whereas ray initials produce radially oriented parenchyma cells. The other divisional strategy is the anticlinal division of radial isodiametric initials to produce new initials and increase the circumference of the cambium as the stem is growing in girth (Hall & Stern, 2012; Mellerowicz et al., 2001) The complete concept of wood formation consists of five recognized developmental stages. They are:(1) the periclinal division of a cambial mother cell into two daughter cells, (2) the increase in the volume of the daughter cells combined with the integration of new polymers into the walls, (3) the formation of different layers of the secondary wall due to deposition of cellulose and non-cellulosic polysaccharides, (4) cell-wall lignification and (5) programmed cell death (Plomion et al. 2001)

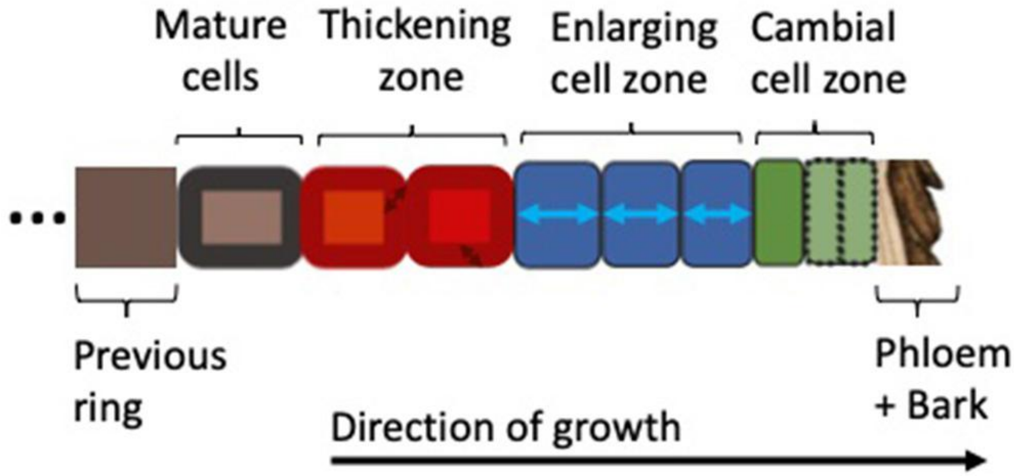


Figure 1: An illustration of wood formation (Eckes-Shephard et al., 2022)

The initial daughter cells produced during wood formation differentiate into specialized cell types for specific functions. Although wood formation in both hardwood and softwoods are identical, the cell types formed are not the same. The cells formed in softwoods are tracheids and parenchyma whereas vessels, fibres and parenchyma cells are formed in hardwoods (Figure 3). Rarely, some hardwood genus such as Quercus possess tracheids. In gymnosperms, tracheids have a dual function to conduct water and provide mechanical support. In angiosperms, vessels conduct water whereas fibres provide mechanical support. Parenchyma cells are in two orientations. The axial and radial parenchyma. The radial parenchyma is in-charge of moving assimilates from the phloem and xylem, whereas their axial counterparts handle vertical transfer from leaves through the stem, to the roots. Additionally, parenchyma cells temporally store starch or lipids and make them available at every new season (Kim et al., 2022; Schmitt et al., 2016).

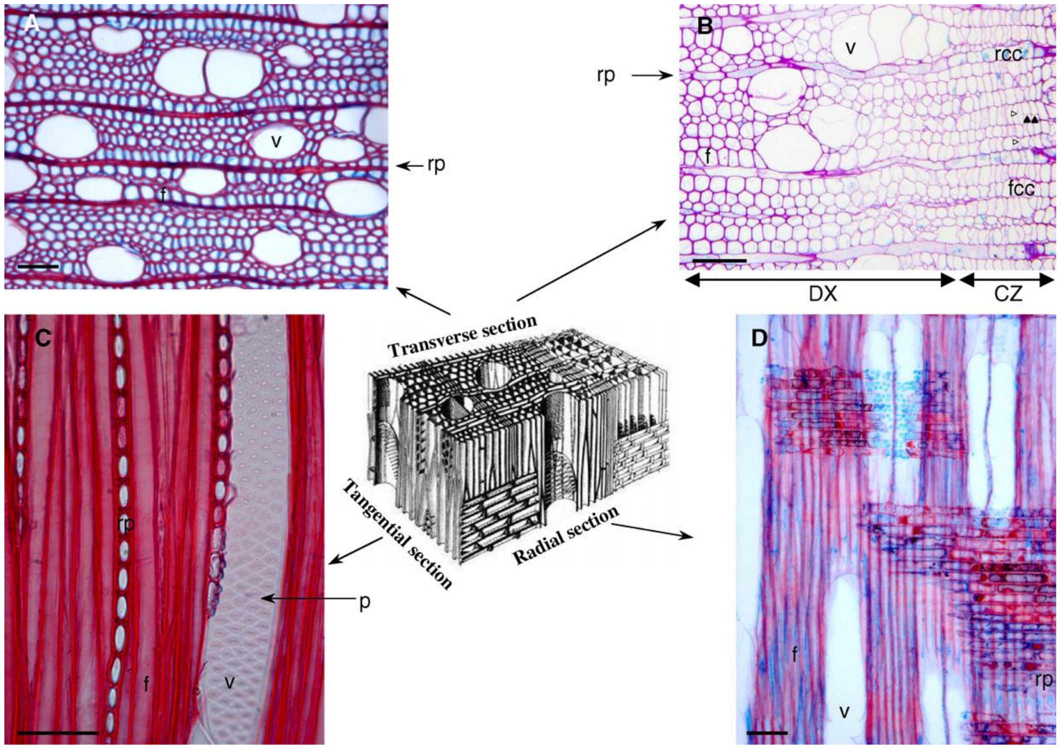


Figure 2: Photo-micrographs of the 3 principal planes of poplar (Populus tremula x Populus alba) wood (Déjardin et al., 2010)

Principal planes of wood surfaces

The surfaces of timber are distinctly classified into the transverse (cross-sectional), radial and tangential. The appearance of wood tissues and their structural characteristics on each surface vary. Similarly, the mechanical properties of wood are not always the same when load is applied on the different surfaces. Macroscopically and microscopically, the uniqueness of the wood surfaces is important for wood identification; the appearance of wood product; and the understanding of wood properties. **The transverse surface** is observed at the end grain of tree trunk or a processed board. On temperate tree trunks, the transverse surface displays the annual tree-rings as concentric circles, with the smallest circle enclosing the pith. All cell types are seen on the transverse surface, but their outlook or visibility to an unaided eye is dependent on species. Typically, vessels are seen as pores, fibres are seen as clustered dots, and the rays align in two or multiple bands running from pith to bark. The transverse surface is the ideal surface to determine the wood tissue proportions and facilitate studies that seek to understand the effect of growth conditions on trees.

The radial surface is observed after making a cut that is perpendicular to the annual tree-ring, from the bark to the pith. This is the surface with straight grain appearance because the fibres are seen in their longitudinal form. Some open chain of vessel elements can be seen as well as cells of ray parenchyma horizontally arranged in bands. **The tangential surface** is revealed by making a flat place cut along the circumference of a tree. The cut should be tangent to the annual tree-rings. This surface usually gives an appealing look to wood products, by exhibiting the unique grain patterns. The tangential surface is comparatively more sensitive to moisture movement (Desch & Dinwoodie, 1996; Shmulsky & Jones, 2011).

2.2 Transformation from initial wood cells to programmed cell death

The initial woody cells formed from the vascular cambium have thin primary cell walls. Afterwards, there is an increase in diameter, setting of secondary wall, and full development of the associated features for the different cell types. Following cell maturity to final size, there is the deposition of very thick secondary cell wall materials. The thicker cell walls empower cells to efficiently perform their mechanical and conductive support functions. The secondary cell walls of fibres and vessels are lignified through lignin in association with hemicelluloses in the cell wall. The process eliminates moisture to form a hydrophobic environment, making the lignified cells rigid and impermeable. The stage after lignification is the programmed cell death.

There is a dissociation of vacuole membrane in cells and a release of hydrolases including Cys and Ser proteases, nucleases and RNases (Courtois-Moreau et al., 2009; Fukuda, 1996; Roberts & McCann, 2000). It is reported that cytosolic pH drops lower to activate cytosolic hydrolases. Cells' cytoplasm is discarded, and there is a disappearance of their nucleus, mitochondria and plastids. It is argued that cell wall lignification is not ultimately related or does not correspond to programmed cell death. This is evident in the fact that parenchyma cells are lignified but they can remain alive to function, including their temporal storage food reserves for utilization during the winter. Later, dysfunctional parenchyma ray cells die, release the phenolic compounds in them and become part of the heartwood (Pallardy, 2007). The synthesized phenolic compounds from dead parenchyma cells diffuse into spaces in cell walls and the lumens of other cell types. This gives peculiar colour to heartwoods of both hardwoods and softwoods. Also, the phenolic compounds enhance the durability of heartwood.

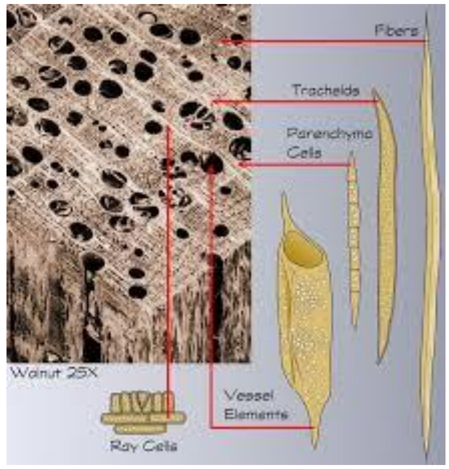


Figure 3: Illustration of tissue types on xylem of hardwoods (image credit: Workshop Companion website).

2.3 The secondary cell wall

The secondary wall of a wood cell is a matrix of about 25% hemicellulose, 50% cellulose, 25% lignin and traces of proteins and pectins. Microscopically, secondary cell walls are built uniquely in three different layers of S1, S2, and S3, mainly consisting of the wood components of cellulose microfibril bundles, lignin and hemicelluloses (Timell, 1967). The angular arrangement of the cellulose microfibril in each layer is different, just as the layers differ in their thicknesses, and chemical constituents (Figure 4). The S2 is the thickest layer (Barnett & Bonham, 2004; Donaldson, 2008). The alternation and angle size of microfibrils within cell wall layers influence the wood rigidity and mechanical strength (Berglund et al., 2020; Cosgrove & Jarvis, 2012; Mellerowicz & Sundberg, 2008; Zhang et al., 2015). The microfibril angle (MFA) is measured in reference to the vertical axis of the fibre. The MFA in the S2 layer is of particular interest because a wider MFA correlates with a lower tensile strength and stiffness (Donaldson, 2008; Hein et al., 2016). Generally, MFA varies radially from pith to sapwood, immediately before the bark. The MFA is higher in the juvenile wood portion, and this explains why they are comparatively of different properties (lower density and different anisotropy) (Hein & Brancheriau, 2011).

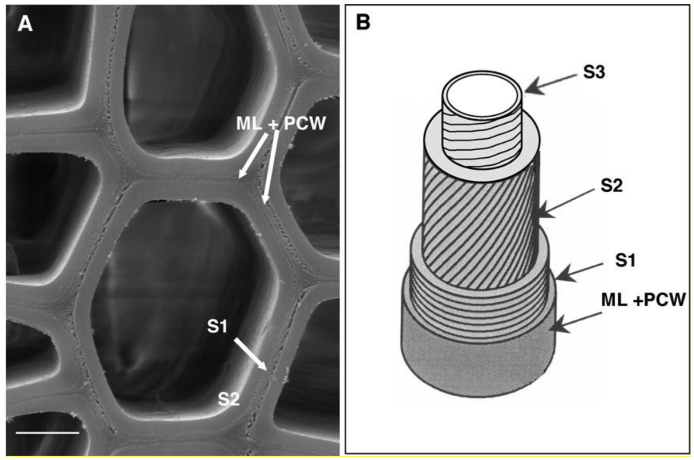


Figure 4: Cell wall structure (Déjardin et al., 2010)

2.4 Plant woody cells

The stem is among the four organs of a plant body. It has been the most focused part of trees by wood industry because of the timber (structural wood, wood-based products, furniture, pulp and paper production etc). The formation of wood has been the result of carbon utilization by trees through photosynthesis. Physiologically, the stem connects the root, and the tree crown, through a complex vascular system. This organ is primarily developed to provide structural support to the tree and to protect the crown for maximum reception of sunshine (Crang et al., 2018). The interest of humans in wood for utilization purposes is just a fulfilment of a secondary purpose.

Generally, plants are composed of cells grouped into three fundamental tissues: parenchyma, collenchyma and sclerenchyma. Plant tissues are cell complexes that have similarity in origin and are designed to perform specific functions. While some tissue can be simple by their nature, xylem tissues are complex consisting of two or more fundamental cell types (Crang et al., 2018).

2.4.1 Parenchyma tissue

Parenchyma tissues are unspecified cell types that carry out plant metabolism. They are simple permanent ground tissues that form the bulk of plant tissue. They are mostly alive, maintain their ability to divide, and possess a primary cell wall. Generally, the roles that parenchyma plays for plants include photosynthesis, wound repair, assimilation of soil nutrients, respiration, storing photosynthate (Beck, 2005; Crang et al., 2018). Contrary to the numerous benefits of parenchyma to plants, their presence in natural timber is a setback during wood utilization. The stored photosynthate in parenchyma serves as food reserves for biodegradation agents such as insects. This suggests that knowledge of the structure of parenchyma in wood pieces should be available to achieve efficient utilization (Crang et al., 2018; Dickison, 2000).

2.4.2 Collenchyma tissue

Collenchyma tissue cells are predominantly found in the cortex of the stems and leaves of the plants and only have primary cell walls that are uneven in thickness. Though collenchyma lacks a secondary wall they are designated to provide mechanical support just as sclerenchyma cells (Crang et al., 2018). This living cell type is just about 1% of occurring plant and they are positioned at locations where some flexibility is needed (Leroux, 2012).

2.4.3 Sclerenchyma tissue

Sclerenchyma tissue cells exhibit great diversity in shape, distribution, origin, function, and structure. Despite the diversity, sclerenchyma cells are equally fundamental, and they are categorized into fibres, sclereids and water-conducting tracheary elements (vessels). They provide structural support due to their rigid cell wall. The lignified cell walls are independent of any turgor built within the cells that are mostly non-living at the mature stage. Fibres are long narrow and lignified thick-walled cells that die when mature. They can be found in all the four major organs of a plant. Fibres are typically not structured to conduct water. However, some species have fibre tracheids that are characterized by sidewall pits that enhance fluid movement.

Fibres appear in clusters in the traditional wood surfaces (Transverse, Radial and Tangential). The tracheary elements are connected to form a conduit architecture for water movement from the roots to the leaves. There are two types of tracheary elements, i.e. vessel elements in hardwoods like oaks or tracheid elements in softwood like pines. Vessel elements of angiosperms are short and wider and are more morphologically varied than the long narrow tracheids in gymnosperms exhibiting less morphological variability (Crang et al., 2018; Dickison, 2000).

Vessel elements connect end-to-end with each other and possess a perforation plate at contact points to facilitate the movement of fluids and other lumen contents. The vessel elements also develop pits on their side walls. The pits spots are free from secondary cell wall thickening (Esau, 1977; Hall & Stern, 2012). The cells that are to form wood fibres undergo pronounced elongation, with length potentially reaching 1.5 mm as in beech (Déjardin et al., 2010).

2.5 Variability in wood

Wood as a renewable material has a complex structure when examined from the three traditional anatomical planes (Figure 2). The characteristics of the individual cell types in the wood surface sections are of diagnostic importance. The biometry and proportion of the cell types (fibres/tracheids, vessels and parenchyma) vary significantly between tree species. For instance, the proportion of ray parenchyma cells in 1 mm^2 is 30%, 9% and 5% for Quercus, Populus and Tilia genera respectively (Leroux, 2012; Maeglin & Quirk, 1984). Also, tissue shape and size differences can be varied within a single tree, depending on the growth conditions and cambial age.

Evidence is the earlywood and latewood variation of cell characteristics within an annual ring. Earlywood formation occurs in spring and early summer months because environmental and soil conditions are most suitable for enhanced cambium activity, and higher growth rate. Comparatively, earlywood cells have wider lumen diameters and thinner cell walls. In contrast, latewood cells have narrower lumen diameters but thicker cell walls. The size and number of all wood cell types, together with the patterns they form at the three surface sections can be modified when trees grow under different factors (Zobel & van Buijtenen, 1989). Some of such modifications lead to the formation of peculiar wood known as reaction wood.

Reaction wood is formed when trees respond to perpetual site conditions such as wind, slope or light to re-orient their trunk and branches, and to generally maintain their balance (Scurfield, 1973). Macroscopically, the transverse sections of reaction woods have pronounced eccentricity. In hardwoods, wood formed under such experience is known as tension wood, and it's formed on the upper side of inclined tree axes. In softwood, reaction wood is termed compression wood, and it's formed on the lower side of inclination. Some of the modifications that occur at the microscopic level include the formation of fewer and narrower vessels in the tension wood (Jourez et al., 2001). Tension wood fibres are remarkably long, unlignified and have a thick inner gelatinous layer that fills up the lumen (Joseleau et al., 2004).

2.6 Historical overview of wood formation

Wood has been used by humans for construction (homes, bridges, ships), tools, artwork, furniture, carts and wheels, and sleighs for centuries (Farmer, 2013). Mai et al. (2022) have reported that Germany is the first territory known to have established a forestry department, and published information on wood properties. This was attributed to a staff named Nordlinger in 1860. In the late 1960s, the first wood formation modelling was developed. Since then, many other models have attempted to improve the knowledge surrounding wood formation in terms of growth patterns, wood quality, and how climate factors influence forest growth (Eckes-Shephard et al., 2022). The established models are applied in different fields including forestry, dendrochronology, and dendroclimatology. Presently, the importance of the study and knowledge of wood formation has increased. The relevance of such study output has increased to the extent that there are arguments to incorporate wood formation in vegetation models for efficient forest management (Fatichi et al., 2014; Friend et al., 2019).

2.7 What regulates wood formation

There is an inarguable scientific remark that wood formation starts from the activities of the vascular cambium layer. The factors that regulate this important process in trees are internal and external. Any factor can be very important depending on the climatic zone in which the tree thrives. Largely, the external factors are environmentally related, and they include temperature, precipitation, humidity, and light (Begum et al., 2018; Gričar et al., 2006; Rahman et al., 2019). The influence of temperature is pronounced in the temperate regions. Lower temperatures initiate the cambial layer’s dormancy in late summer. Cambial activation starts in spring when the temperature starts to be adequate (Silva et al., 2023). Although species effect on wood formation has been admitted, Cabon et al. (2020) generally estimated the optimum temperature to activate cambium activity for trees in temperate regions to be around 5 °C.

Regarding precipitation or drought, the absence of rainfall for 3 to 4 months in the tropics causes cambial activity to cease (Rahman et al., 2022). This phenomenon is indifferent to the Mediterranean climate. Drought stops cambial activity until suitable soil moisture is reached (Vieira et al., 2020). The internal factors that influence cambial layer activation are hormone-related. The activation of the vascular cambium and the differentiation of the xylem are partly regulated by chemical hormones such as auxin, cytokinins, gibberellins and ethylene. The tips of shoots and roots are characterized by hormones such as indole-3-Acetic Acid (IAA) and hormonal signals. Hormones either function independently or jointly to be effective when responding to environmental events. These have been confirmed in hardwoods species such as poplar and aspen (Fu et al., 2021; Junghans et al., 2004; Love et al., 2009; Mellerowicz et al., 2001; J. Nilsson et al., 2008; Saks et al., 1984).

2.8 The Hungarian wood industry

Despite the shift in forest land use distribution in favour of protective forests, back in the year 2000, about 69% of the Hungarian forest land area was under timber production. This forest coverage can generate about 80 % (7.6 million m^3) of targeted timber estimated for sustainable forest management purposes (Nemzeti Élelmiszerlánc-biztonsági Hivatal, Erdészeti Igazgatóság, Budapest, 2018). This signifies the relevance of the forest estates within the territory to the Hungarian economy. For decades, the timber growing stock in Hungary has been increasing yearly. Yet, the timber produced has been insufficient to meet the wood industries' demand. The annual timber volume increment of 13 million cubic meters could not meet the wood demand from the industry in terms of species diversity. This reported observation was even after the Hungarian land reforms, where the wooded forest lands were bequeathed to the state. Partly, the insufficient timber was because many of the standing trees were diseased and of poor quality. Again, since the 1950s, timber production, consumption and importation values indicated that almost half of Hungary's timber needs can only be met by importation. Mrackova et. al. (2021) reported that about 69% of the Hungarian wood industry relied on imported hardwood raw and semi-finished products to survive as smaller customer-oriented manufacturers.

The practice of importing timber for the Hungarian wood industry cannot be a sustainable strategy for sourcing wood. Wood importation has remained an economic burden as the prices of foreign timber keep increasing. The availability of imported timber in Hungarian markets is reducing. Practically, it's difficult to measure the consumption of hardwood in a particular country territory. Published values are always estimated, and not current (Forbes et al., 1993; Mračková et al., 2021). The characteristics of the international hardwood markets keep changing (Grzegorzewska & Sedliačiková, 2021). Unsustainable sourcing of wood will most likely be crushed by the increasing concern for a cleaner and greener global environment. Addressing the outcry would call for reviews and tightening of timber trade regulations. Therefore, there is no future guarantee that wood for the industry can sustainably be sourced through importation. It is against this background that many territories including Hungary are targeting to re-develop their indigenous hardwood timber resources for the future. This will safeguard the quality of life and the availability of desired wood products.

2.9 Wood density

The use of wood and wood products is inevitable because the application of wood constantly covers a wide range of human needs. Generally, wood materials from different species are not the same in terms of their properties and are therefore suitable for different uses. Several decades ago, the key physical indicators for segregating wood from different species, especially for trade and utilization, included density (literary how heavy the wood is) and colour. Wood density is characterized by the ultrastructure of the wood cell, particularly fibres or tracheids, the quantity of cell wall material deposited, the lumen cavities of individual cells, the size of vessel elements, the proportion of wood tissues, the extractives and moisture content. Strongly, wood density is correlated to its strength properties, and relates to shrinkage, pulp yield, mechanical properties and other characteristics (Funada et al., 2016; Kollmann et al., 1975; Panshin & Zeeuw, 1970).

A tree's growth rate and its influence on wood density has been a concern well investigated. In many instances for hardwoods and softwoods, trees with faster growth rates have their wood densities reduced (Moya & Tomazello, 2007; Naji et al., 2011; Nilsson et al., 2021). This is attributed to, among others, the fact that enhanced growth did not lead to enough deposition of cell wall material. Contrary, other studies found that growth rate had almost no effect on wood densities. Typical among species with such observation are those with diffuse-porous ring structure (Zobel & van Buijtenen, 1989).

Silviculturally, the effect of mixed-species stands is not just limited to producing resilient forests and enhancing forest ecosystem benefits. There is evidence that mixed-species stands influenced the quantity and quality of wood produced in these forest stands (Pretzsch & Rais, 2016). In research with European beech and Calabrian pine grown in the Mediterranean climate, Russo et al. (2020) found that the mixed-species forest stands produced wood with improved properties than counterparts in pure-species stands. In another study involving pubescent oak (*Quercus pubescens* WillD.) in Slovenia, it was found that mixed-species stands influenced the wood density of the grown tree species (Krajnc et al., 2021). The authors, however, acknowledged that the magnitude of the mixed-species influence was the least, compared to other factors. In a German study of several hardwood species including sessile oak (*Quercus petraea*), mixed-species stands were found to have produced denser wood (Pretzsch & Schütze, 2021).

2.10 Brief notes about Turkey oak

2.10.1 Geography

Turkey oak is originally indigenous to the southern, central and southeastern parts of Europe, and with extended coverage into southeastern Asia (Danielewicz et al., 2016). The species tolerates a range of soils, though prefers warm climates. Turkey oak therefore mainly dwells on southern slopes and can quickly colonize open areas (Eaton et al., 2016). Turkey oak is unfriendly to strong and delayed frost. The species is characterized as drought tolerant and can thrive on shallow soils that are poorly developed. Eventually, they improve such soils by preventing erosion and enhancing soil conservation (Mert et al., 2016). The species is a pioneer category. Its saplings sprout well and are fast-growing. The matured trees of Turkey oak between ages 60 - 80 years are mostly associated with diseases that slows down their growth.

Notable to Hungarian forests are 2 varieties of the Turkey oak species. They are *Quercus cerris* and *Quercus austriaca*. The variety *Quercus austriaca* exhibits better growth and wood properties. It is also known to tolerate air pollution, and therefore a preferred choice for urban greening (Eaton et al., 2016; Pearman et al., 2002).

2.10.2 Morphology

Turkey oak trees may reach a height of about 30 meters on a favourable site. Commonly, about 50% of its total height could be a trunk free from branches (Eaton et al., 2016). Its average diameter at breast height is around 50 cm, with the bark taking up to 25% of the total cross-sectional diameter depending on the tree's age. The outlook of the Turkey oak tree carries an aesthetic value. Hence, it's a favourite urban afforestation tree species (Pearman et al., 2002). Typical as it is with most tree species, the trunk of Turkey oak can be significantly influenced by silvicultural practice (Guilley et al., 2004; Toïgo et al., 2015). The trunks are visibly associated with longitudinal frost ribs. Harvesting Turkey oak trees after age 60 is recommended as a best practice to avoid losing their wood quality due to age-related diseases (Eaton et al., 2016).

2.10.3 Genetic diversity of oak populations

Historically, it is reported that oaks naturally thrived in three restrictive locations. The refuge niches are the Iberian, Italian and the Balkan peninsula. The thriving areas for oaks changed 7000 years ago, before covering most of their present-day locations. The recolonization of oaks has contributed to their genetically diverse distribution (Petit et al., 2002). A close observation of the various refuge niches indicates that the Balkan peninsula area had the highest genetic diversity and exhibited special traceability (Bagnoli et al., 2016). According to the authors, three clusters of oak were distinctively identified based on genetic and geographic indicators. The first is the Western cluster comprising the Italian peninsula and the North-western Balkan region. The second is the Central cluster that comprises the central and southern Balkans. The third is the Eastern cluster covering groups in Anatolia and the Middle East. In Italy, research found Turkey oak to be closely related to *Quercus suber* by two common haplotypes. Then it was inferred that the haplotypes were possible evidence retained from their ancestral connection. In Anatolia, two different gene pools were identified with low genetic diversity in the northern region and high genetic diversity in the south-central region. *Quercus crenata* Lam., commonly called false cork oak, scattered in Italy, France, Slovenia and Croatia is a notable hybrid from *Q. cerris* and *Q. suber*. Other hybrids are less frequent and found among the eastern Mediterranean oaks. They include *Q. libani* Oliv. (*Q x Libanerris*), *Q. trojana* Webb. (*Q x schneideri* Viehr.), *Q. pubescens* (*Q. x baenitzii* A. Camus), *Q. brantii* Lindl, *Q. infectora* Oliv. and *Q. ithaburensis* Decne (Ozer, 2014). Again, a study in Italy developed a synthetic map of genetic variability for Turkey oak to support conservation strategies (Bertolasi et al., 2023).

In Hungary, a similar study on the natural Turkey oak population found four genetically distinct groups; two from the Balkans area, one from Hungary and one outlier group (Lados et al., 2024). The authors observed that while the Balkan group was more diverse. The Hungarian group was genetically consistent; however, these findings probably indicated a common refuge origin. Similar research is ongoing for Turkey oak populations to support conservation and climate adaptation strategies of forestry (Lados et al., 2024).

2.10.4 Climate impact on Turkey oak geographic distribution

The effects of climate change on future vegetation and ecosystems have been a matter of concern for decades. The responses from temperate forests to climate change scenarios are uncertain. There have been projections that range from severe decline to increased growth, and varied wood quality . There have also been predictions related to species shifts across forest ecosystems or mitigation in tree species distributions. In a climate-species simulation study, a model (CCLM4-GEM2-ES; rcp8.5) predicted that Quercus' survival and growth could be affected. Species in this genus would significantly decrease for southern and southeastern edge populations including Hungary (Fréjaville et al., 2020; Mátyás, 2021; Sáenz-Romero et al., 2017). In general, the most crucial climate variables were shown to be precipitation and temperature (Führer et al., 2013). Other studies also narrowed the causal factor to soil moisture (Kovács & Czigány, 2017). Ecologically, Turkey oak can be used to rehabilitate soils, promote conservation and increase the biodiversity of an area. Additionally, the species is quite resistant to wildfire. In Turkey, a study to estimate the potential distribution of Turkey oak has been conducted with the current and changing climate as simulation factors. According to the study outputs, Turkey oak was demonstrated the preferred reforestation or afforestation species in Turkey (Mert et al., 2016).

2.11 Brief wood characteristics

Turkey oak wood exhibits traits that are similar to other oak species. Unfortunately, the wood of Turkey oak is associated with factors that limit its acceptance into the furniture industry. Comparatively, Turkey oak easily cracks has reduced dimensional stability and has low durability (Bajraktari et al., 2018a). Naturally, Turkey oak appeals less (Tolvaj & Molnár,

2006) and has gluing difficulty (Lavisci et al., 1991). The gluing problem is attributed to the wood's surface properties and pH. In effect, Turkey oak has become a lesser-used timber species. It is predominantly used for energy purposes (firewood) despite its potential as a green bio-material.

Commercially, another challenge that hinders Turkey oak from attaining higher value status is the associated numerous stains. The occurrence of stains is due to the possession of wood extractives such as tannins (Lavisci et al., 1991). On the cross-sectional surface, Turkey oak has a large pale sapwood, whereas the heartwood is dark grey (Tolvaj & Molnár, 2006). The heartwood is reddish, a suitable color for veneer application. It is one of the few species that has the presence of a 'blackheart' heartwood discoloration (Bajraktari et al., 2018a).

2.11.1 Macroscopic features

A common characteristic for hardwoods grown in the temperate is the earlywood to latewood proportionality and its associated vessel size variation. The heartwood portion is dark reddish brown whereas the sapwood portion is wide, light grey and sometimes yellowish, clearly demarcated than heartwood. In addition, many Turkey oak stems display a possible formation of false heartwood that looks brownish-red (Budakci & Cinar, 2004). The juvenile wood could cover about 15 - 20 annual rings which are variably wider in width. The wood is ring porous and the freshly cut heartwood smells sour.

2.11.2 Physical parameters

A study on wood materials from coppiced Turkey oak stands revealed greater variability in shrinkage. This observation is an inarguable trait in the unpruned stump originated wood specimens of Turkey oak. The same study found a dry density range of 0.57 – 1.06 g/cm^3. The shrinkage on the tangential face was 11.1%, radial shrinkage was 6.6%, and volumetric shrinkage was 18.5% (Monaco et al., 2011).

2.11.3 Chemical properties

Some of the main chemical components reported in literature are cellulose, hemicellulose, lignin, extractives and ash content. The cellulose content ranges from 48.1 to 54.0%, hemicellulose content which is predominantly xylans ranges from 17.8 to 24.9%. The hemicellulose is comparatively low in arabinose content and acetyl groups. The lignin content ranges from 22.85 to 26.45%. Extractive content in Turkey oak from 2.3 to 6.99 %. This value is comparatively low compared to other oak species and has been used to explain the low durability of the species and its plain yellowish-white colour (Deaconu et al., 2023a; Fodor & Hofmann, 2024). The ash content ranges from 0.41 to 0.93% . Turkey oak wood contains reduced amounts of polyphenols and tannins (Bajraktari et al., 2018b). The author reported an average total phenolic content of 310.5 mg GA/g of extract; 25.6 mg CE/g of extract; 64.3 m CE/g of extract. Hence, there is usually very slow movement of extractives to the wood surface (Lavisci et al., 1991).

2.11.4 Steaming effect

There have been research efforts to normalize some of the challenges associated with Turkey oak. The challenges are associated with drying (dimensional instability, checks and cracks) and appearance (non-uniform colour). The aims were to improve the quality of Turkey oak and to encourage its acceptability for valuable industrial use. A successful example of such studies is the applicable use of thermal treatment to reduce the equilibrium moisture content (EMC) and to unify color variability (Todaro et al., 2012). Steaming increased the permeability of Turkey oak in a decade-long study, especially in the sapwood. This was attributed to the variation in anatomical structure (Rezaei et al. 2024). However, there have been some reported trade-offs while improving other properties. Steaming is reported to decrease modulus of elasticity and compression strength of Turkey oak because the process modifies the chemical components (Cetera et al., 2016).

2.11.5 Wood defects

There are defects associated with Turkey oak logs and their processed wood. Some defects are age-related, whereas others are natural. There are defects associated with processing and drying techniques (Deaconu et al., 2023b). Natural defects include frost ribs, false heartwood, and ring shakes. The age-related defects are mostly stains (Bajraktari et al., 2018a).

2.12 Soil as a natural resource

Any country's natural resource resources include soils, which comprise the soil-water-near surface atmosphere, the geology, relief and biota (National Atlas, 1989). Therefore, rational uses of land and proper management of soils are essential practices needed to enjoy normal soil functions sustainably. In the long term, this boosts territorial economies, protects the environment, and guarantees rural development (Stefanovits, 1992). Historically, humans have benefited from two specific and special soil traits. The first special trait is the multifunctionality of soil in terms of fertility and productivity. The second special trait is the resilience of soils in terms of the diverse nature and renewability of the soil. The dependencies on these two key traits are affected by the soil's natural conditions at any moment and the prevailing socio-economic situation (Várallyay, 2015a). However, the unstable relative importance accorded to these production levels is influenced by the socio-economic situation and in some cases, forced political decisions (Csete & Várallyay, 2004). Mostly, these identified influences conflict with guided and rational management approaches. In effect, there is over-exploitation of soil, reduction in its efficiency, and environmental deterioration (Várallyay, 2007).

2.13 Hungarian soils

In Hungary, the uses of land for primary, secondary and tertiary agricultural production including forest plantations have an economically significant influence. Spatially and temporally, Hungarian soil is characterized by a wide diversity. This is attributed to the varied factors that formed the soils in the different locations within the Carpathian Basin. A large part of the land is covered by Quaternary (Pleistocene), Holocene, and more recent geological deposits. These are loeses, aeolian, alluvial and colluvial deposits that exhibit varied stratification, texture, structure, hydromorphic character, mineral and chemical compositions (Stefanovits, 1992). The Hungarian weather has been a matrix of Continental, Atlantic and Mediterranean climates. The reported average annual precipitation is 500-550 mm whereas the potential evapotranspiration is estimated to be 800-900 mm. These values create a water deficit which could occasionally be counter-balanced by surface runoffs, seepage and groundwater flow from the hilly grounds and higher altitudes that surround the lowlands (National Atlas, 1989; Palfai, 2000).

Generally, there is evidence suggesting that the natural conditions of soils in the Carpathian Basin are suitable for rain-fed biomass production (Lang et al., 1983; Csete & Várallyay, 2004: Várallyay, 2015b). The observation is irrespective of the spatial and temporal variability of the soils. Soil degradation practices, extreme moisture regimes (floods, waterlogging, over-moistening and drought sensitivity) and negative changes in biogeochemical cycles of elements (plant nutrients and environmental pollutants) are setbacks to favorable agroecological potential.

2.13.1 Classification

The Hungarian soil has been divided into nine major categories. These nine categories are classified (named) as: 1) skeletal, 2) shallow soils influenced by the parent material, 3) brown forest chernozems, 4) salt-induced soils, 5) meadow soils, 6) peat soils, 7) swampy forests soil, 8) alluvial and 9) slope sediment soils (Michéli et al., 2007). The focus of this present study is on the brown forest soil category (Braunerde). This major soil type is formed under forest vegetation and is usually with ochre (light-colored) surface horizons. Their main subtypes are soils with or without distinct subsurface horizons. The subtypes are Chernozem brown forest soil which represents the following soil transitions: the brown earth soil representing the classic leached Ramann brown forest soil; the most commonly found brown forest soils with clay illuviation; the stagnant brown forest soil which has a slowly permeable clay accumulation horizon; the banded brown forest soil formed with a sandy parent material; and the acidic, non-podzolic, high acidic brown forest soil. The skeletal soils are weakly developed under limited soil formation constraints. This soil type consists of a broad range of soils including a rocky base with shallow depth of fine earth to deep sandy soils with a 30cm layer of humus content.

Figure 5: Soil map of Hungary (Varallyay, 2015b).

Notes on Figure 5

1. Blown sand. 2. Rendzinas. 3. Brown forest soils with clay illuviation. 4. Pseudogleys. 5. Brown earths (Ramann brown forest soils). 6. Sandy brown forest soils with thin interstratified layers of colloid and sesquioxide accumulation. 7. Chernozem brown forest soils. 8. Chernozem-type sandy soils. 9. Pseudomyceliar (calcareous) chernozems. 10. Lowland and meadow chernozems. 11. Meadow and lowland chernozems with salt accumulation in the deeper layers. 12. Solonchaks and solonchaksolonetzes. 13. Meadow solonetzes turning into steppe formation. 14. Solonetzic meadow soils. 15. Meadow soils. 16. Peats. 17. Soils of swampy forests. 18. Alluvial soils.

2.14 Soil moisture extremity

The dependency of agriculture and forest plantations on soil moisture is undoubted. In the Hungarian plains, which is the deepest part of the Carpathian Basin, soil water is likely to be the determining factor for food security and environmental safety. This local prediction alongside the global future prediction by the IPCC regarding decreased precipitation and increased atmospheric temperature by more than 1.5 ºC is a concern (IPCC, 2018). In effect, improving water use efficiency will be a paramount issue among biomass production fields, for rural development, and to provide hope for environmental protection. Additionally, the task of controlling the soil water regime is a must-considered practice for sustainable production and development (Palfai 2000; Somlyody 2000; Várallyay, 2011). Water resources in the Pannonian plains are not only limited but also spatial and temporally variable, even on a micro-scale level. The average annual atmospheric precipitation across Hungary for the past 100 years is presented in Figure 6.

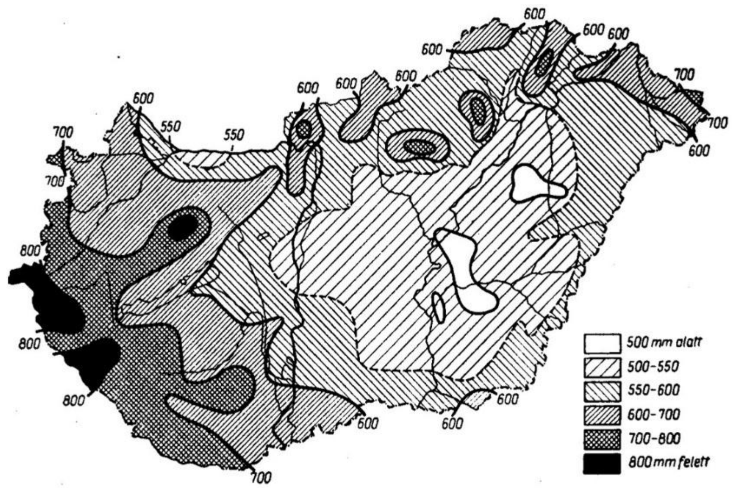


Figure 6: Geographical distribution of average annual precipitation in Hungary over the last 100 years (Várallyay, 2015b).

Generally, good-quality soils are those with adequate capabilities of storing natural water, adequate aerations, and endowed with suitable nutrients . Such types of soil contribute to meeting plants' water requirements for growth. In Hungary, a monitoring system that was based on a 5-step model existed in collaboration with a detailed physical/hydro-physical database (Várallyay, 2015a). On the contrary, poor-quality soil is poorly drained. Their subsurface waters have high salt content, unfavorable composition of ion, with a threat of harmful salination processes. In the areas around Kecskemet that fall under the Danube-Tisza Interfluve sand Plateau, dry years are consecutive and there is over-exploitation of subsurface waters. The ground water-table in such areas is deeper and results in increased aridity. Relatively, the proportion of good quality soil in the area is marginal (Várallyay, 2011).

Chapter 3. Materials and methods

3.1 Location of Hungary

Hungary is geographically positioned between latitude 45°45' and 48°35' and longitude 16°06' 22°54' east. The territory of Hungary is estimated to be 93,030 km^2, situated deep within the hydro(geo)logically closed Carpathian Basin (Figure 8). The land mass is about 1% of Europe. Approximately half of Hungarian land is below 200 m above sea level, whereas 2% of the land is above 400 m. The neo-tectonic activities and peri-glacial processes during the quaternary period are the explanatory factors for the present topography of Hungary. The lower elevated lands are covered by aeolian and alluvial materials whereas the high lands are derived from older sedimentary and volcanic rocks (National Atlas, 1989).

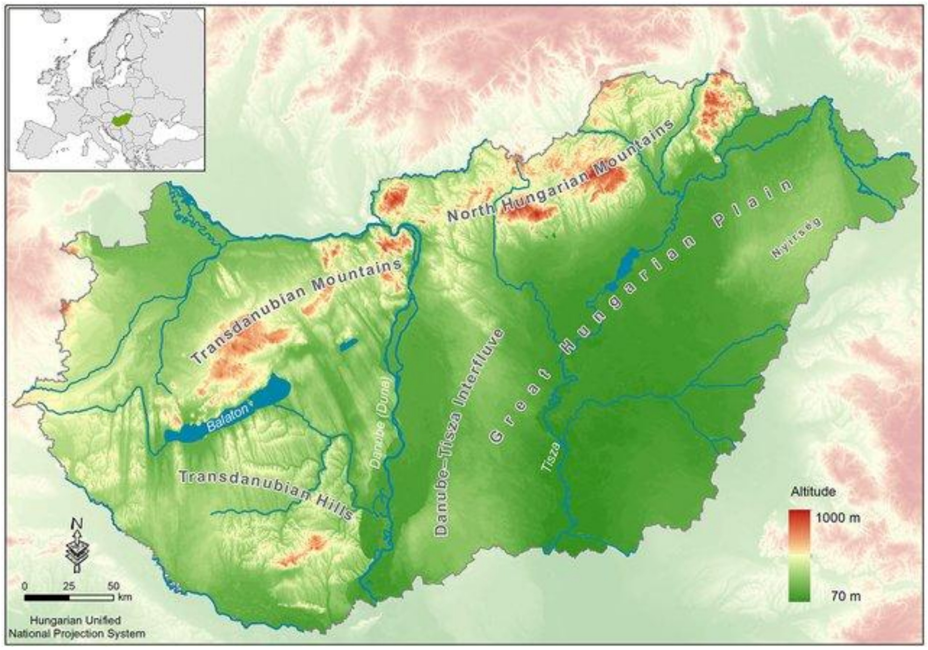


Figure 7: Hungary location and general geographical conditions (Bozsik & Koncz, 2018).

3.2 Study sites (County level) and sampling design

This comparative study collected Turkey oak materials from 5 counties in Hungary (Figure 8). The counties are Vas (sites include Vasvár, Hosszúpereszteg, Bögöte, Egyházasrádóc), Gyor-Moson-Sopron (areas include Sopron, Nagycenk, Ivan), Komárom-Esztergom (around Pilis Mountain range), Bács-Kiskun (areas include Kisszallas, Melykut, Janoshalma, Nyarlorinc), Baranya (areas include Ibafa, Hetvehely). These sites are expected to have varied growing conditions that influence growth for the trees in the near-natural forest environment. Essentially, the varied growth conditions are related to key climate variables (precipitation and temperature). Notably, the western part of Hungary comparatively moist than the central and eastern part (Fekete et al., 2023; Gadermaier et al., 2024; Várallyay, 2015a). The eastern and central parts are also known to have leached-sandy soil. The number of trees sampled per county varied in proportion to areas of stand volume. The ages of the trees, which were estimated by careful counting of the annual rings, ranged between 38 to 129 years (Table 1).

Table 1: Brief information on sampled trees from counties and key climate variables.

Locality (Counties)	***No. of trees***	***Diameter range (cm)***	***Age range (years)***	***Annual Precipitation (mm)***	***Temperature_max in July/August (°C)***
Bács-Kiskun	6	16-27	38-65	500 – 600	29
Komárom-Esztergom	4	35-48	63-81	550 – 700	32
Baranya	4	30-34	77-81	600 – 800	31
Gyor-Moson-Sopron	4	26-30	85-98	600 – 800	32
Vas	12	15-54	63-129	600 – 800	33

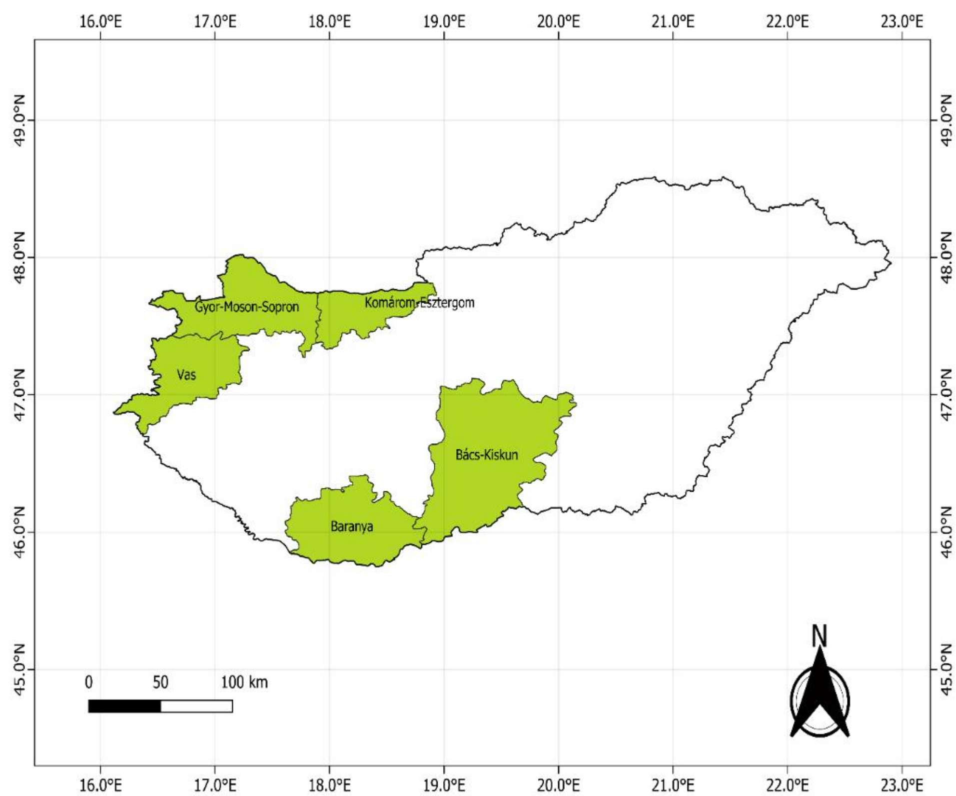


Figure 8: Location of selected counties in Hungary.

3.3 Study site (within Vas County) and sampling design

The study was conducted using wood materials from Vas County in western Hungary, which shares its west boundary with Slovenia (Figure 10). Turkey oak trees were randomly harvested from four different sites within the county. A description of the sampled trees is presented in Table 2. There are two types of soil quality that supported the stands' growth. The plots categorized as 'Good Soil' had a rusty brown forest sandy soil of about 60-100 cm deep. It was reported to have high fertility, good structure, balanced nutrients levels, adequate drainage and balanced pH. The 'Poor Soil' category had rusty brown forest loamy soil of about 40-100 cm dept. Additionally, the Poor Soils sometimes had low fertility, poor structure, easily compacted and waterlogged (Tóth et al., 2007; Várallyay, 2015a). On each soil type are plots of pure and mixed species planting of Turkey oak. In the mixed-species plot were other broad-leaf species ash and hornbeam species. Unfortunately, the genotype of the trees selected for this study is not readily known.

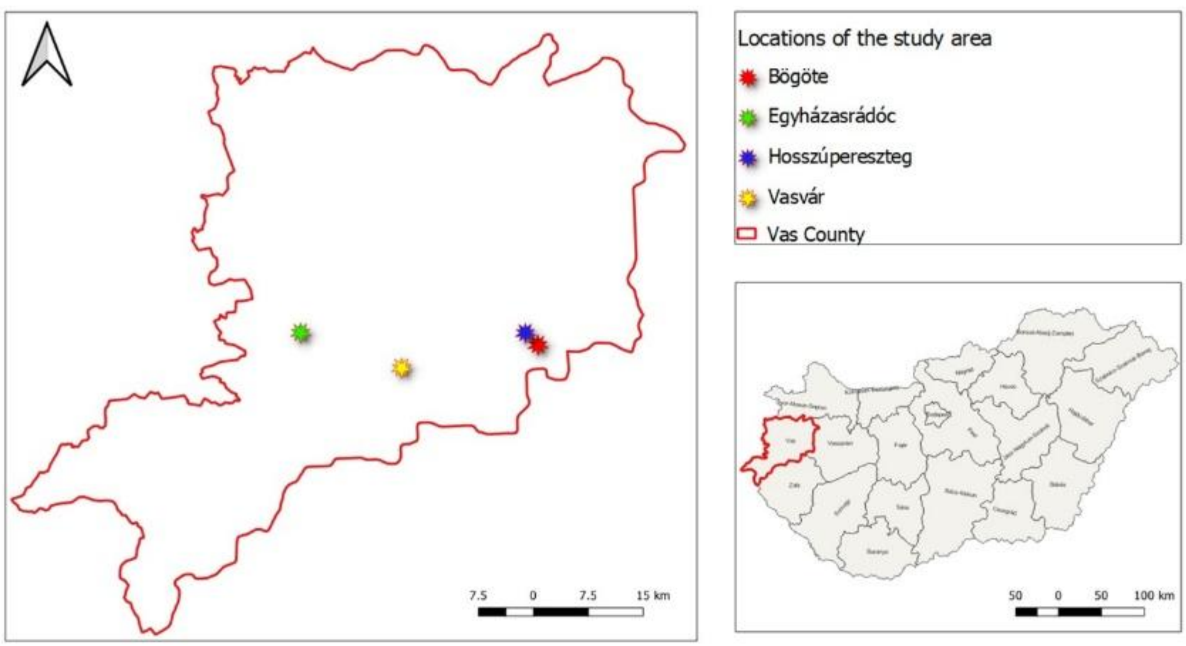


Figure 9: Study sites within Vas County of Hungary.

Table 2: Description of study locations and materials. DBH – diameter at breast height.

Location	***Soil quality***	***Stand composition***	***Diameter (DBH) cm***	***Age (yr)***	***Brief soil description***
Bögöte	Good	Mixed-species	46	87	Rusty brown forest sandy soil. 60-100 cm deep
Bögöte	Good	Mixed-species	50	78	
Egyházasrádóc	Poor	Mixed-species	54	87	Brown forest loamy soil with slack water. 40-60 cm deep
Egyházasrádóc	Poor	Mixed-species	31	76	
Egyházasrádóc	Poor	Mixed-species	42	87	
Hosszúpereszteg	Good	Pure-species	54	129	Rusty brown forest sandy soil. 100 cm deep
Hosszúpereszteg	Good	Pure-species	54	123	
Vasvár	Poor	Pure-species	15	69	Rusty brown forest loamy soil. 60-100 cm deep
Vasvár	Poor	Pure-species	27	70	
Vasvár	Poor	Pure-species	23	68	
Vasvár	Poor	Pure-species	20	67	
Vasvár	Poor	Pure-species	18	69	

The mixed species are broadleaved-broadleaved species of Sessile oak (*Quercus petraea*), Hornbean (*Carpinus betulus*), Robinia (*Robinia pseudoacacia*) and European Ash (*Fraxinus excelsior*). The soil quality classification is based on a study (Várallyay, 2015).

Chapter 4. Heartwood-sapwood proportion and annual tree-ring characteristics

4.1 Introduction.

The availability of oak trees in forest ecosystems has been characterized by numerous benefits because of their functional properties. Ecologically, resilient species are known to enhance conservation and rehabilitation with their nutrient-cycling ability (Camponi et al., 2022; Woś et al., 2023). This function contributes to the forest ecosystem's health and productivity (Gadermaier et al., 2024). The canopy structure of oak, by shape and size, allows sunlight to get through to the forest understory layer. This helps with fast leaf litter decomposition and supports regeneration in plants grown below the oak trees' canopy layer. The oak biomass produced does not only store carbon but also serves as raw materials for the wood industry.

Presently, climate change and its effects on both flora and fauna cannot be doubted. There are scientific and inter-governmental efforts to address the global climate challenges that have been caused by humans' actions and inactions. The prediction by the end of this century is an increase in global mean temperature between 2.4 and 6.4 ^{o}C (IPCC, 2023). Turkey oak is reported to be thermophilic (can thrive in higher temperatures) and drought-tolerant (Fuchs et al., 2021; Kunz et al., 2018; Móricz et al., 2021). In Hungary, Turkey oak is the fourth most important hardwood species by standing volume and area coverage. Meanwhile, the wood of Turkey oak is less used with respect to value-added applications. Notably, the species is known to be suitable for numerous technological applications including wood-floorings.

Human-aided interventions to improve ecosystem resilience are available but expensive to adopt. The Hungarian government hopes to manage its forest resources to enjoy long-term ecological, economic and social benefits. Clearly, this national intent is continuously threatened by climate change. Over two decades, how the wood of Turkey oak grown in the Hungarian environment has been anatomically influenced by growth conditions including climate is not fully understood. For instance, parenchyma cells play very important roles such defense and storage of photosynthate for living trees. However, the same parenchyma cells become a primary weak point for wood during utilization. This is because the reserved photosynthate they carry becomes foods for biodegradation agents like insects.

In regards, vital information such as parenchyma content, is inadequate. Knowledge of vessel elements quantity, the fundamental structure for moisture movement in hardwood species, is inadequate. This study was carried out to determine the tissue proportion (parenchyma, vessel elements and fibres) in wood of Turkey oak grown in different localities.

4.2 Materials and methods

The study site information and sampling methods have been presented in Chapter 3, sections 3.2 and 3.3

4.2.1 Sample preparation

Logs of the 12 harvested trees were conveyed to the University of Sopron for processing and subsequent transfer into the wood anatomy laboratory. The test samples for the annual ring study were extracted from the point on the stems known as the diameter at breast height (dbh). Two discs of about 4 cm thickness were taken from each stem for anatomical studies. For the measurement of annual ring characteristics and sapwood-heartwood proportion, the discs were left to naturally dry to about 20% moisture content. The drying of discs facilitated their sanding operation. Sanding papers of increasing grit sizes (from 180 to 600 grit size) were engaged on an electric-powered sanding machine (Figure 10) to produce clean and smooth cross-sectional surfaces.

Figure 10: Sanding of wood disc

4.2.2 Sapwood-heartwood proportion determination

The sampled discs had the typical distinct heartwood and sapwood portions, and their boundaries were not ambiguous. The cross-sectional surfaces were sanded. Four cross-diameter measurements were taken on each disc with a simple measuring tape (Figure 11).

The heartwood portions were measured as a cross diameter and averaged. The averaged sapwood portion was deduced subsequently. The heartwood-sapwood proportions were expressed as a percentage of the mean cross-diameter value in the equation below. The sapwood proportion was obtained by simple subtraction (Diaz-Maroto et al., 2017).

$$Heartwood\ proportion = \left(\frac{mH}{mD}\right) * 100\%$$

Where,

$mH\ (mm)$ = mean heartwood

$mD\ (mm)$ = mean cross-diameter

Figure 11: A disc of Turkey oak with a typical distinction between heartwood and sapwood.

4.2.3 Data capture and analysis for annual rings

The sanded discs were scanned using a flatbed scanner (CanonScan LiDE 110, Canon, Japan) into image files. The image files were loaded into ImageJ computer software

(National Institute of Health, United States of America) (Abràmoff et al., 2004) for measurements. The fixed scales from the images were configured into the ImageJ software for correct measurement.

The parametric data was organized in Excel (version Office 365, Microsoft, United States of America) software and analyzed in the R statistical package (www.r-project.org; R Development Core Team, 2021). An analysis of variance (ANOVA) was used to compare the mean values for the measured variables. Any significant differences found between the mean values were further tested with Tukey Honest Significant Difference (post hoc) at 95% confidence. The analyses in the entire dissertation followed the same pattern.

4.3 Results

4.3.1 Heartwood-sapwood proportion

The heartwood-sapwood portions for all stems of the Turkey oak logs were distinct. The heartwoods were darker brown than the sapwood (Figure 11). Turkey oak tree from Vas County had the highest mean heartwood proportions of 75% followed by the wood materials from the Baranya County area with 71%. The Turkey oak wood from the Komárom-Esztergom and Bács-Kiskun area had the highest mean sapwood proportion of about 40% whereas counterparts from Szombathely had the lowest proportions Figure 12. The means values for both heartwood and sapwood proportions compared across localities indicated that the site location had a statistically significant influence on the heartwood-sapwood proportions ($p < 0.05$).

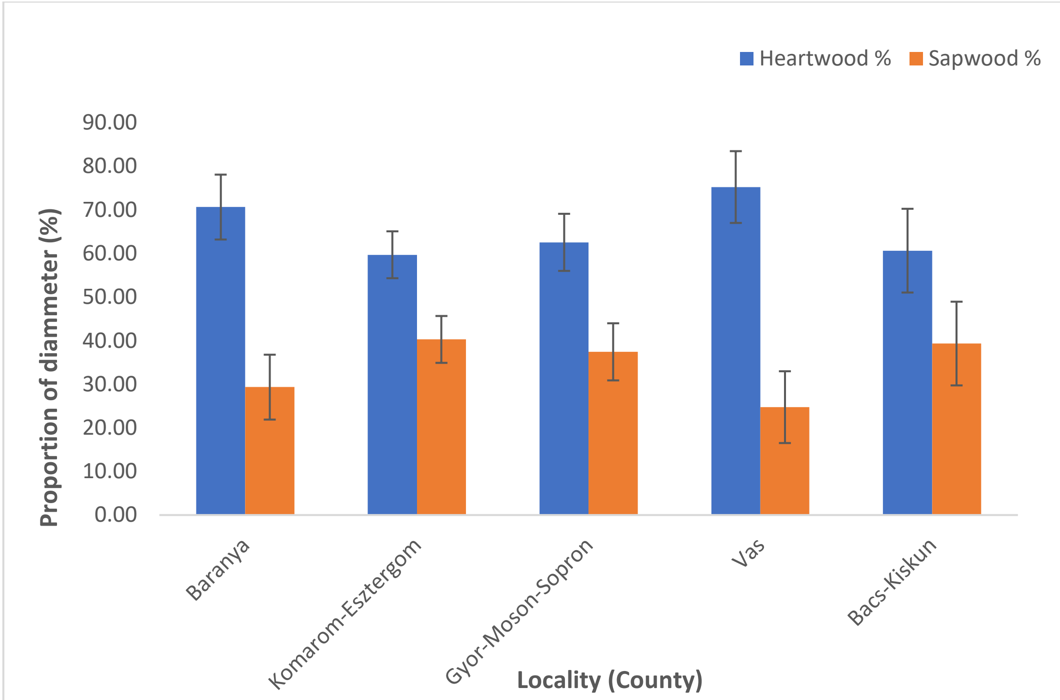


Figure 12: Heartwood-Sapwood proportion (%) for Turkey oak grown in five counties in Hungary.

Regarding materials from plots within Vas County, the mean values for heartwood and sapwood proportions were very similar. The sapwood portion was generally about one-fourth of the cross-sectional diameter (Figure 13). The differences in their mean values were not statistically significant under any of the single factors. A combination of the factors, however, had a slight statistical significance over their mean values (Table 3).

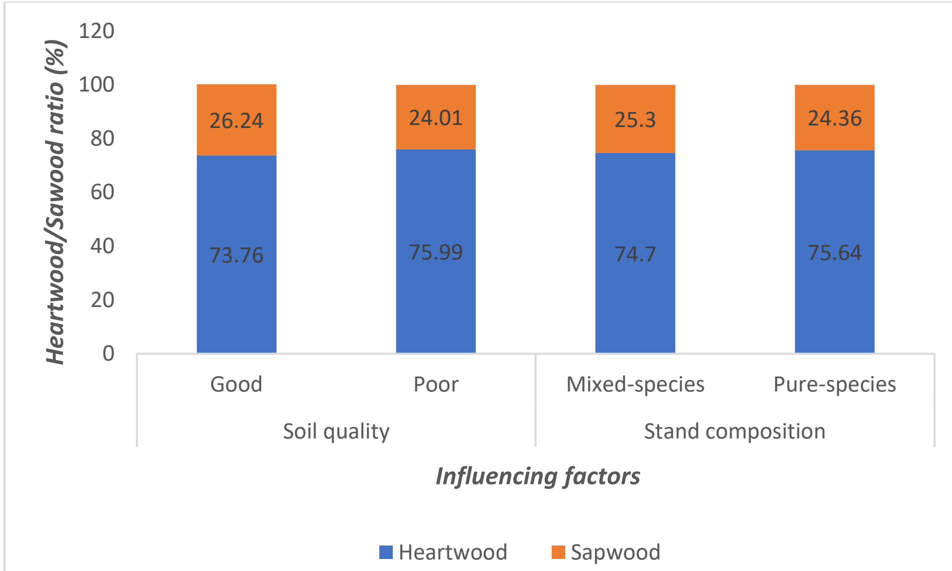


Figure 13: Heartwood and Sapwood proportion (%) by soil quality and stand composition in the Vas County.

Table 3: P-values from ANOVA for the measured annual tree-ring width and sapwood-heartwood proportion as separately influenced by soil quality and stand composition in the Vas County.

Factors	***Heartwood (%)***	***Sapwood (%)***
Soil quality	0.494	0.448
Stand composition	0.765	0.786
Combination of Soil quality and Stand composition	0.040 *	0.037 *

* – significant, ** – high significant, *** – highly significant

4.3.2 Annual tree-ring across study sites (per county)

Radially, the annual rings were categorized into juvenile (first 15 rings from the pith), heartwood and sapwood. The mean annual tree-ring width ranged from 1.32 to 3.68 mm (Table 4**Error! Reference source not found.**). Comparatively, the annual rings were wider at the juvenile portions, followed by the heartwood and then the sapwood. On the contrary, wood materials from the Komárom-Esztergom area had an irregular pattern of wider heartwood annual rings. The Juvenile portion of the Baranya materials recorded the widest mean annual ring width (3.68 mm). A wider mean annual ring width for heartwood was recorded for Komárom-Esztergom materials, and also for sapwood. Additionally, wider annual rings also had a distinct greater latewood portion than earlywood. The differences in the reported mean values were statistically significant (Table 44).

Table 4: Average annual ring width (mm) for Turkey Oak from locations in Hungary. In parentheses, are the standard deviations.

Location (County)	***Juvenile***	***Heartwood***	***Sapwood***
Gyor-Moson-Sopron	2.81 (1.18)^{a}	1.58 (0.60)^{a}	1.53 (0.82)^{a}
Vas	3.01 (0.69)^{a}	1.92 (0.54)^{b}	1.32 (0.34)^{a}
Komárom-Esztergom	1.40 (0.43)^{b}	2.46 (0.77)^{c}	2.08 (0.86)^{b}
Bács-Kiskun	2.51 (0.68)^{c}	2.25 (0.65)^{c}	1.88 (0.60)^{b}
Baranya	3.68 (1.02)^{d}	2.36 (0.96)^{c}	1.59 (0.48)^{a}
p-value	<0.05	<0.05	<0.05

Superscript letters $^{a, b, c, d}$ represent outputs of Tukey post hoc test in ANOVA. Different superscripts indicate that the compared mean values are significantly different.

4.3.3 Annual tree-ring width per soil quality and stand composition in Vas County.

The annual tree-ring width (TRW) generally decreased from pith (the juvenile) to the sapwood portion on both good and poor soils (Table 5). The age of sampled trees for the study was unfortunately not the same. Therefore, for easy comparison, the tree-rings were grouped under categories of juvenile, heartwood and sapwood. The grouping was done with the assumption that some trees might have developed heartwood earlier than others due to the age inconsistency of the sampled trees. The mean values for annual TRW at the juvenile region ranged from 2.47 mm to 3.29 mm; it ranged in the heartwood between 1.64 and 2.32 mm; and in the sapwood from 1.16 to 1.60 mm. The effect of the combination of factors has been presented in **Error! Reference source not found.**. Statistically, soil quality had little s ignificance on the TRW at both the juvenile and sapwood portions. Stand composition rather had little statistical significance on only the TRW in the heartwood portion (Table 6).

Table 5: Mean values for tree ring-width for wood portions as influenced separately by soil quality and stand composition in Vas County. In parentheses are the standard deviations of the mean.

Factor	***Category***	***Juvenile wood (mm)***	***Heartwood (mm)***	***Sapwood (mm)***
Soil quality	Good	2.47(0.7)	2.07(0.6)	1.60(0.4)
	Poor	3.28(0.5)	1.84(0.5)	1.18(0.2)
Stand composition	Mixed	2.62(0.7)	2.31(0.6)	1.50(0.4)
	Pure	3.29(0.6)	1.64(0.2)	1.16(0.1)

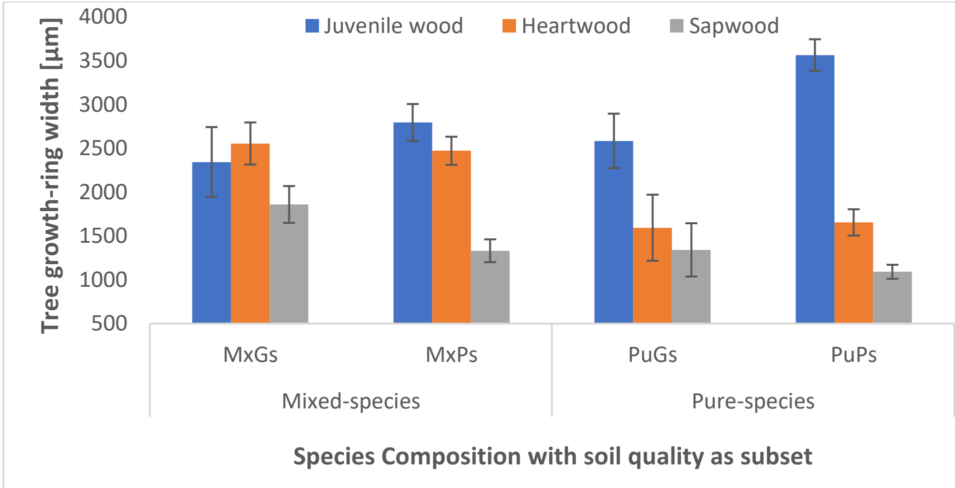


Figure 14: Mean annual tree ring width as influenced by a combination of the soil quality and stand composition in Vas County. Radially grouped portions are Juvenile wood, Heartwood and Sapwood. Mx - mixed-species, Gs - good soil, Ps - poor soil, Pu - pure-species. The error bars are for the standard deviations.

Table 6: P-values from ANOVA for the measured annual tree-ring width as separately influenced by soil quality and stand composition in the Vas County.

Factors	***Juvenile wood ring width***	***Heartwood ring width***	***Sapwood ring width***
Soil quality	0.048 *	0.508	0.038 *
Stand composition	0.097	0.024 *	0.052
Combination of Soil quality and Stand composition	0.073	0.141	0.029 *

* – significant, ** – high significant, *** – highly significant

4.3.4 Earlywood-latewood characteristics

The tree ring widths for Turkey oak trees planted among other broad-leaf hardwood species (mixed stands) were larger than trees from pure stands (Table 7). This observation is true irrespective of soil type. Similarly, the early- and latewood widths recorded were larger for Turkey oak trees from mixed stands. Earlywood (EW) is wood formed after vascular cambium is reactivated in spring. It is characterized by larger-size vessel elements to facilitate the transport of water and minerals and thinner-walled fibres. Latewood (LW) is characterized by smaller-sized vessel elements and thicker-walled fibres to provide mechanical support. Analysis of variance (ANOVA) indicates that the differences between the mean values presented are statistically significant (with p-values of 0.05) for stand composition. Soil quality showed a significant influence only on the ring components (EW and LW).

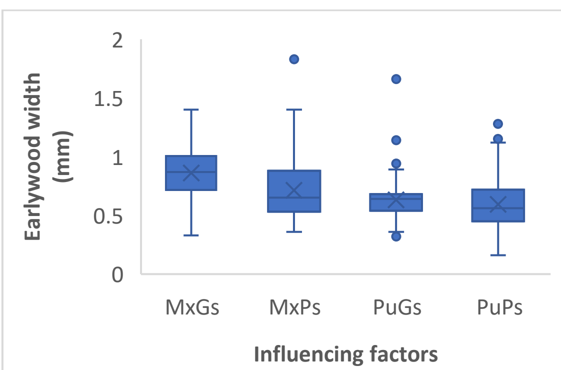
Table 7: Mean values of tree-ring portion characteristics for Turkey oak from Vas County in Hungary.

Influencing factors	***Earlywood width (mm)***	***Latewood width (mm)***	***Total tree-ring width (mm)***
MxGs (Bögöte)	0.9(0.2)[a]	1.4(0.6)[a]	2.3(0.7)[a]
MxPs (Egyházasrádóc)	0.7(0.2)[b]	1.5(0.8)[a]	2.2(1.0)[a]
PuGs (Hosszúpereszteg)	0.6(0.1)[c]	0.9(0.4)[b]	1.6(0.5)[b]
PuPs (Vasvár)	0.6(0.2)[c]	1.1(0.9)[c]	1.7(1.1)[b]
p-value	0.05	0.05	0.05

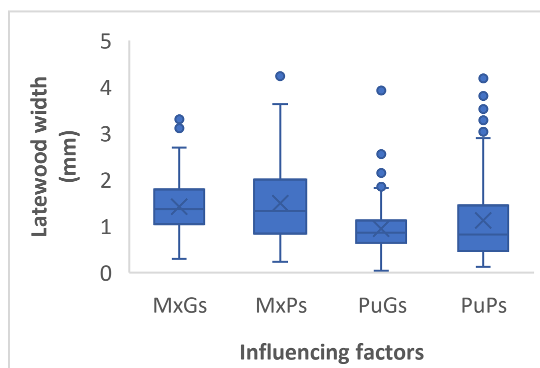
Superscript letters [a, b, c] - represent the output of Tukey post hoc test in ANOVA. The values in different superscripts are significantly different.

The dispersion of values of TRW and widths of ring components (EW and LW) for trees from the four plots have been presented in plates a), b) and c) of Figure 15.

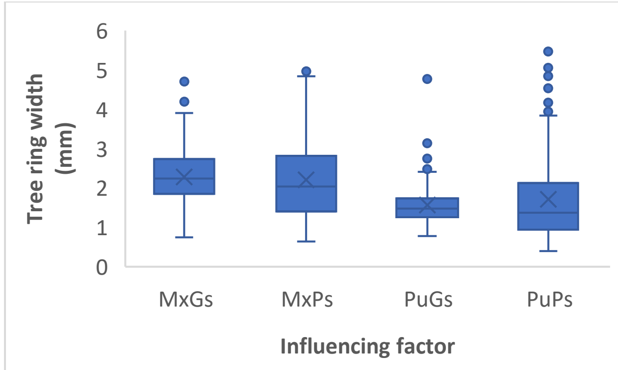
The trees from the poor soil sites were dispersed a little wider than their counterparts from the good soil sites. TRW for trees from mixed species plots on good soil exhibited a narrower spread. EW sizes were also the least spread for trees from pure species plots on poor soil.



a)



b)



c)

Figure 15: Boxplot for earlywood width (a), latewood width (b), tree-ring width (c) of Turkey oak harvested from Vas County in Hungary. Mx - mixed-species, Gs - good soil, Ps - poor soil, Pu - pure-species.

The coefficient of variation for the EW, LW and TRW are presented in Table 8. The highest ring width variation was observed in the LW width of trees from pure species plots grown on poor soil. The proportions of EW and LW to TRW are presented in Table 9.

The EW proportion ranged from 8 – 98% whereas the LW proportion ranged from 2 – 92%. Expectedly, the LW proportion of the juvenile wood part was larger than that of the heartwood and sapwood portions.

Table 8: Coefficient of variation for EW, LW and TRW of Turkey oak from four different sites in Vas County in Hungary.

Influencing factor	***Earlywood width***	***Latewood width***	***Tree-ring width***
MxGs (Bögöte)	0.26	0.44	0.32
MxPs (Egyházasrádóc)	0.34	0.58	0.46
PuGs (Hosszúpereszteg)	0.22	0.45	0.30
PuPs (Vasvár)	0.33	0.82	0.62

Table 9: Proportion of earlywood and latewood in tree ring width for Turkey oak from Vas County in Hungary.

Influencing factor	***Earlywood %***	***Latewood %***
MxGs (Bögöte)	19 - 71	29 - 81
MxPs (Egyházasrádóc)	14 - 70	30 - 86
PuGs (Hosszúpereszteg)	18 - 80	20 - 82
PuPs (Vasvár)	8 -79	21 - 92

4.4 Discussion

4.4.1 Heartwood-sapwood proportion

Heartwood formation in woods has numerous advantages including enhancing its durability (Bamber, 1976). Durability is key for the numerous uses of Turkey oak, especially for flooring. The formation of heartwood in studied trees varied among sites. Generally, the findings from this study agree with information presented earlier (Bajrakatri et al., 2018a; Corcuera et al., 2004; Diaz-Maroto et al., 2017). It can be inferred from the findings that Turkey oak trees harvested could serve as suitable stem wood supply for the Hungarian saw-millers.

4.4.2 Annual tree-ring width across County

The mean TRW values reported for Turkey oak in this study agree with many other studies (Rybníček et al., 2006; Wang et al., 2021; Zalloni et al, 2018a). The relationship between annual TRW and mean density for hardwoods like oak is known. The wider annual TRW at the juvenile and heartwood regions suggest higher mean ring density because of the larger latewood width (Guilley et al., 1999; Zhang et al., 1993). In regards, forest management strategy for oak rotation cycle has been over 100 years, just to ensure that oak wood produced has evenly narrower bands (Spiecker, 2021). The observed variation in annual TRW, beside cambial age, can be associated with genotype and soil moisture conditions (factors which were unfortunately not covered in this study).

4.4.3 Annual tree-ring width per soil quality and stand composition in Vas County

Annual TRW studies are fundamental because they can predict the performance of trees and encode the prevailing ecological information (Čufar et al., 2014; Godoy-Veiga et al., 2021; Kovács & Czigány, 2017; Ladányi & Blanka, 2015). The findings of this study on ring width agree with literature (Corcuera et al., 2004). The comparatively higher annual TRW making up juvenile wood across sites can be attributed to the initial vigorous growth of seedlings, saplings, and young trees. The thinner TRW in the sapwood region in both stands can be attributed to the recent alteration in the aged cambium over the years. In a study on *Quercus faginea*, soil quality was found to be a significant source of variation in annual TRW (Sousa et al., 2018).

4.4.4 Earlywood-latewood characteristics by silviculture

The study findings for tree ring characteristics are comparable with the literature (Rybníček et al., 2016, Mészáros et al., 2022). The tree-ring width variation of up to 0.62 is an indication of crucial influence of inter-annual climate variability on the radial growth of trees (Mészáros et al., 2022). There are possible complex eco-physiological interactions between Turkey oak trees and their growing conditions (Čater and Levanič, 2015, Hafner et al., 2015, Zalloni et al., 2018b, Roibu et al., 2020). The 'Pure species + Poor soil' condition that supported sampled trees produced the most varied TRW. This observation suggests that any growth predictions for Turkey oak grown under such conditions may differ than reality. Further is also suggest that Turkey oak trees grown on poor soils can assume any growth rate. On the other hand, the same observation guarantees that there may be rigorous cambial activity for radial growth at the matured stages of Turkey oak stand.

The larger TRW recorded for Turkey oak trees grown in mixed species can be attributed to the benefits from the improved of soil conditions due to mixed species planting (Guo et al., 2023). Such a stand composition enables Turkey oak to realize its potential as a fast-growing species (Eaton et al., 2016). Nonetheless, the variations could be attributed to other non-considered factors such as species genotype. The analysis of variance proved that stand composition is a main influence on TRW.

4.5 Conclusions

Part of the expected output of Hungarian Forests Management are sustainable supply of wood for their industries and to encourage valuable utilization of lesser-used species. Turkey oak has withstood ecological conditions over the years. The drought-tolerant species exist across different sites in Hungary from young to mature stands. On the agenda of valuable utilization, properties of the Turkey oak wood across Hungary need to be fully understood from anatomical to mechanical strength characterization. The heartwood and sapwood portions for all Turkey oak trees in this study were distinct. Studied trees from the west and south-west of Hungary (Vas, Baranya and Gyor-Moson-Sopron) exhibited greater heartwood than counterparts from the Komárom-Esztergom and Bács-Kiskun.

The observations could be associated with the varied amount of precipitation in the separate regions. With no genotype information about the Turkey oak trees harvested for the study, other studies in that direction must be considered to support knowledge of the sources of variation for effective forest management. Regarding the effect of selected silvicultural practice, it can be inferred from this study that stand composition is an important factor when considering forest plantations for Turkey oak. Stand composition is also a source of significant variation for vessel characteristics in latewood portions. The co-habitation of Turkey oak with other tree species will not only improve biodiversity and ecosystem but also the wood quality of Turkey oak.

Chapter 5. Relating annual tree-ring to climate variable

5.1 Introduction

Several factors can contribute to the growth of trees from their seedling stage to maturity into harvestable timber. Such factors are biological, environmental, silvicultural, and often a combination of these. Each of these factors embodies a collection of variables such as genetics, soil conditions, precipitation, temperature, thinning, photoperiod, pruning, seedling health etc. Climate variables are known to work best together rather than in isolation. It is rather difficult to single out, for instance, the effect of only temperature on growth. This is because temperature has influences on other growth factors such as soil moisture (Creber & Chaloner, 1984). However, precipitation and temperature have been established as the main variables influencing tree growth in forest ecosystems. Fortunately, these two variables are most readily measurable, centuries ago.

Presently, global environmental degradation and changing climate can never be denied. Climate change and global warming have been crisis issues for decades now. It is unsure what the future holds for forest ecosystems even though there are significant inter-governmental efforts to address these issues. Climate models from reliable literature sources suggest that there will be an increase in mean surface temperature. This will affect the severity of conditions, how often conditions will occur, and how long conditions will persist (Fischer & Schär, 2010; Hoerling et al., 2012; IPCC, 2018). The same reports predict more frequent and prolonged heatwaves and drought, respectively. Forests and trees are likely to react to the changing climate conditions differently per their existing growing condition, and physiological limits (Allen et al., 2010).

Regarding environmental challenges and their effect on society and forests, the story is not different in Europe (Schweingruber & Nogler, 2003; Alexandrov et al., 2010; Di Filippo et al., 2010). The forest susceptibility to climate change has increased with individual species' adaptive capacities threatened. Eventually, forest productivity could either be reduced or increased to affect the expected timber in terms of quality and quantity (Lindner et al., 2010).

The timber industry in Hungary has played a major role in its economy, though wood production from Hungarian forests plays a minor role (Csoka, 1997). This is because a large percentage of the timbers for wood and construction in Hungary are imported softwoods.

Turkey oak is an important species to the Hungarian forestry from an economic and ecological perspective. The species of sub-Mediterranean origin has been described as drought-tolerant (Mészáros et al., 2022). This growth characteristic tips the species to be a promising forest plantation material amidst future climate predictions (Thurm et al., 2018).

Undoubtedly, tree rings carry important records of conditions that the tree has survived, including cases of fire, pest attacks, and climate influence (such as precipitation and temperature). Several studies have investigated the correlation of precipitation and/or temperature with trees' radial growth (Zywiec et al., 2017; Heilman et al., 2021; Stangler et al., 2021; Mirabel et al., 2022; Yocom et al., 2022). Similar studies on *Quercus sp.* can be traced to research works several decades ago (Kleine et al., 1936). Current climate-growth relationships studies have focused on *Quercus petraea* [Matt.] Liebl. (sessile oak) and *Quercus robur* L., (pedunculate oak) (Friedrichs et al., 2009; Čufar et al., 2014; Stojanović et al., 2018).

Turkey oak is a ring-porous deciduous hardwood, that exhibits distinct sapwood-heartwood proportion and a denser biomass (Popa et al., 2013; de Rigo et al., 2016). Valuable utilization of all timber material depends on extensive knowledge of its properties, including any possible variability. Again, its wood has exhibited some similar desirable characteristics when compared to other preferred oaks. For instance, Turkey oak is similar in appearance to noble oak and would be preferred for interior cabinet works. In regards, Turkey oak can receive a valuable utilization status. This study examines *(i)* the earlywood-latewood width and variation in Turkey oak grown under 4 different conditions within Vas County in Hungary, *(ii)* the dendrochronological correlation between annual tree-ring Turkey oak trees and climate variables (precipitation and maximum temperature). The findings from this study can help to support a decision on developing forest plantations of the drought-tolerant Turkey oak for timber production in Hungary.

5.2 Materials and Methods

The annual tree-ring measurements for Turkey oak were from the study in chapter 4, section 2, sub-section 3. A representation of images for the Turkey oak rings from the various sites in Vas County is shown in Figure 16.

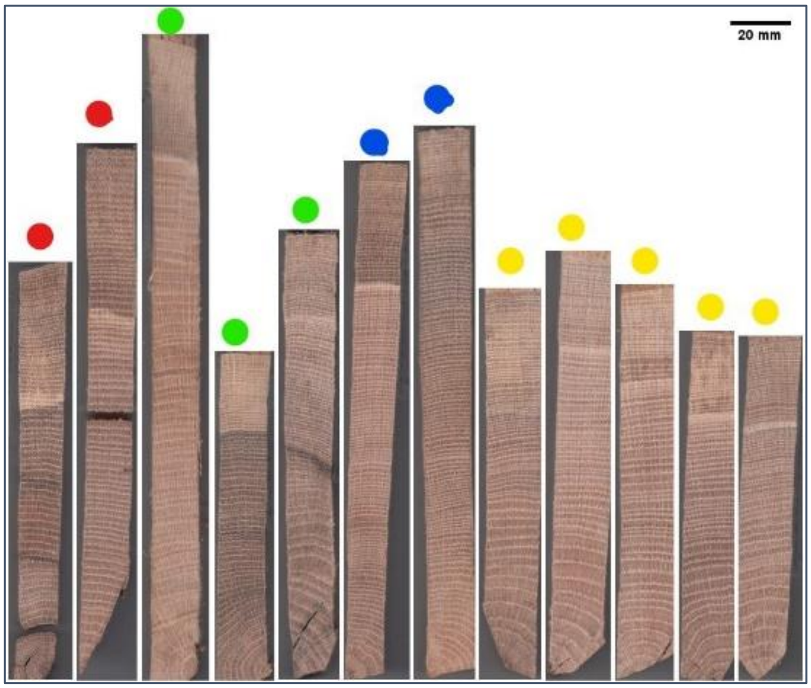


Figure 16: A collection of images of tree rings from sampled Turkey oak from Vas County in Hungary. Red=MxGs, Green=MxPs, Blue=PuGs, Yellow=PuPs.

5.2.1 Climate data

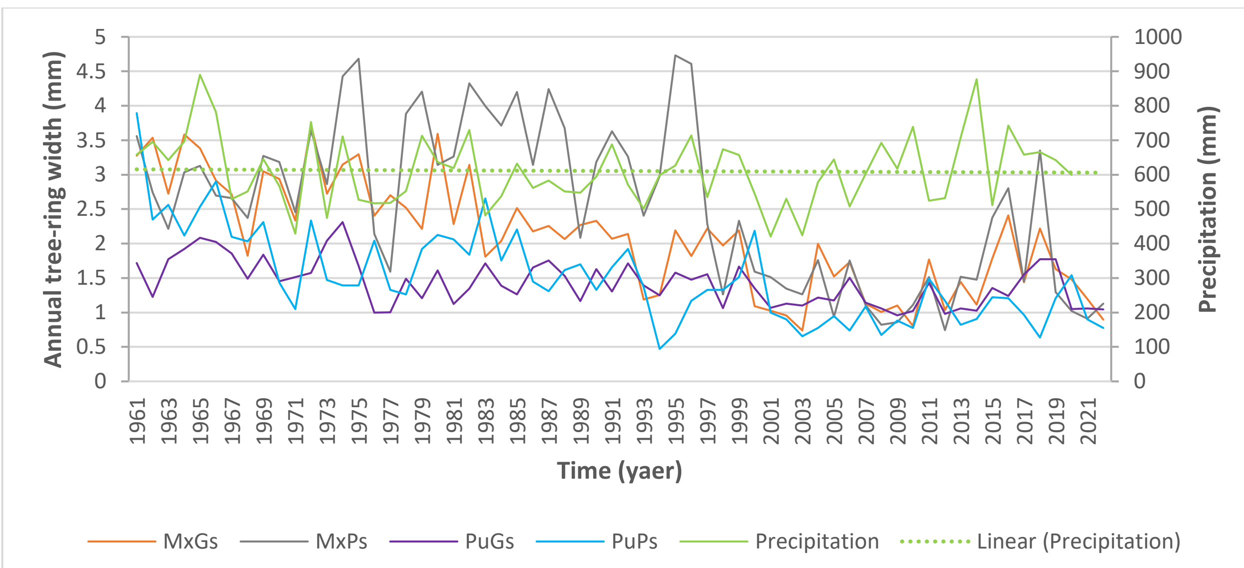
The climate data (mean annual precipitation and maximum temperature of the growing season) for the Vas County were retrieved from the Hungarian National Metrological Service database for the period between 1961 to 2021. The study concentrated on maximum temperature because of the prediction that the mean value for air temperature will increase in future. Based on knowledge of the actual growing season for oak (Perkins et al., 2018), the climate data was concentrated between April and October. The precipitation and temperature of the previous year were correlated with the tree-ring of the current year (Mészáros et al., 2022).

The data curing, analysis and image visualization were done in Excel spreadsheet (version Office 365, Microsoft, United States of America). A correlation was conducted in the R Statistical programme.

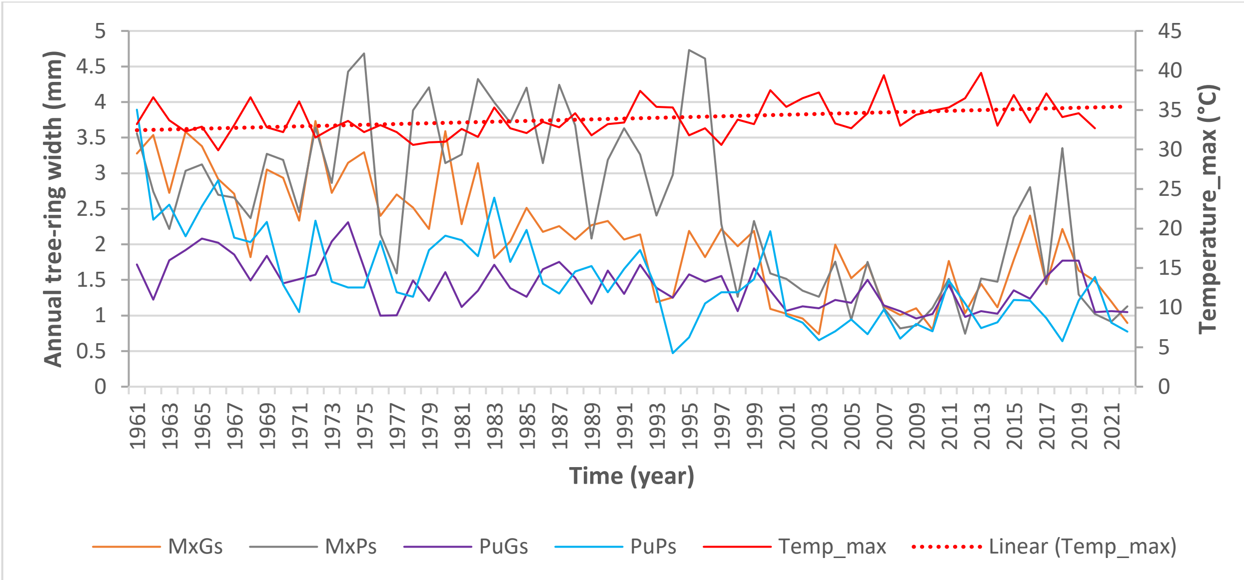
5.3 Results

5.3.1 Relationship between tree ring width and two climate variables

The pattern of precipitation positively affected the annual tree-ring. However, for about three decades ago, the TRWs for trees from all plots have been narrower with the irregular pattern of precipitation (Figure 17A) and temperature (Figure 17B) recorded within the analyzed period of 1961 to 2021. Mixed species plot on good quality soil visibly mimics the pattern for precipitation recorded except for the years between 2005 and 2015. A similar observation cannot be seen when TRW is chronologically associated with maximum temperature. Also, it is evident that the maximum temperature is slightly increasing (Figure 17B). Generally, there is not a well define pattern observed when TRW is associated with the climate variable.



A)



B)

Figure 17: Reserve chronology of annual tree-ring against precipitation (A), maximum temperature (B) from April to October for Turkey oak trees from Vas County in Hungary. Mx – mixed species, Gs – good soil, Ps – poor soil, Pu – pure species, TRW – tree-ring width.

The TRW correlated with maximum temperature and precipitation has generated the following outcomes for the analyzed period 1961 to 2021. There was a positive correlation between precipitation and tree RW (Figure 18). Correlations for wood from the four plots were weak to moderate (0.09 – 0.32) within the individual growing sites. On the contrary, the correlation between maximum temperature and TRW is negative. This means that an increase in maximum temperature will result in a decrease in tree-ring width. Across the four plots, the positive correlation was moderate (-0.32 to -0.42) as presented in

Table 10.

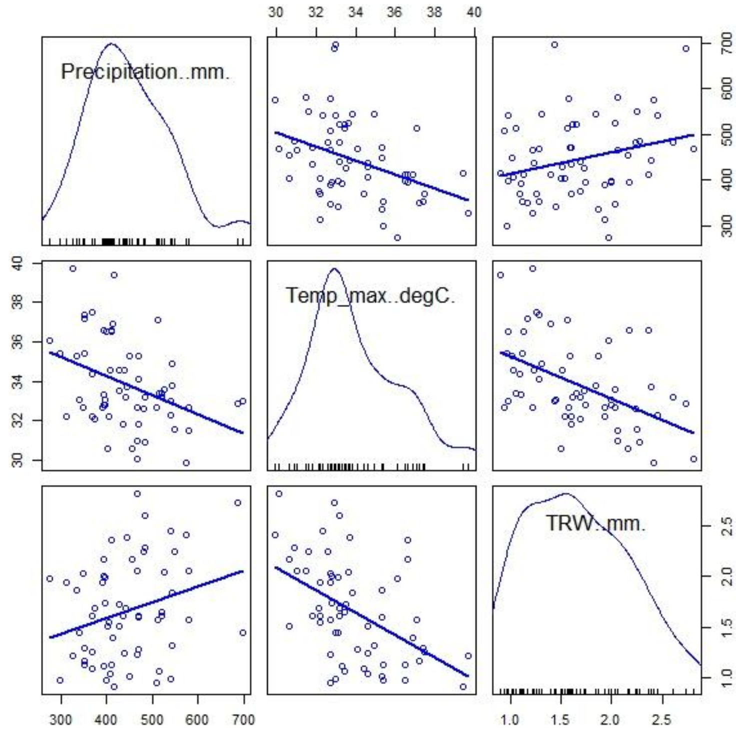


Figure 18: Scatter-plot matrix of precipitation and temperature_max with annual tree-ring width.

Table 10: Correlations co-efficient of temperature and precipitation with annual tree-ring width under various influencing factors.

Climate variable	***MxGs***	***MxPs***	***PuGs***	***PuPs***
Precipitation	0.1317	0.0913	0.2181	0.3235
Maximum Temperature	-0.3953	-0.4169	-0.3186	-0.4227

Mx – mixed species, Gs – good soil, Ps – poor soil, Pu – pure species.

Future climate forecast gives enough justification for focused research on tree growth, especially on species identified as drought tolerant such as Turkey oak. The advantages of establishing mixed-species stands in a forest ecosystem cannot be over-emphasized. Recent studies confirm that mixed-species planting enhances soil suction and moisture redistribution, improves soil properties and enzymatic activities, and expands soil carbon stocking (Ni et al., 2018; Gong et al., 2021; Guo et al., 2023).

Ideally, affordable forest restoration programs can focus on alternative silvicultural approaches to improve the soil instead of applying fertilizers at a cost. This study provides scientific information to support the campaign and adoption of this forest management method for growing the drought-tolerant Turkey oak into quality timber in Vas County in Hungary. It is important to reiterate that the genotypes of the sampled oak trees for this study are yet to be known.

5.4 Discussion

5.4.1 Climate and tree-ring width relationship

The effect of changing climate on forests has been a concern for professionals in diverse disciplines including wood scientists. Particularly is the changing climate effect on trees growth and annual wood formation. This study on the association of TRW precipitation and temperature shows a irregular climate-growth pattern between the period of 1961 and 2021. The study findings agree with other studies which focused on forests in the Mediterranean region (Hayles et al., 2007; Planells et al., 2009). The decrease in TRWs from the 1980s was observed for all four investigated stands/plots concerning both precipitation and maximum temperature. Comparatively, TRW for trees grown as mixed species roughly followed the pattern of precipitation and but not maximum temperature recorded (Figure 17). This observation has also been reported for Turkey oak and Sessile oak (*Quercus petraea)* (Mészáros et al., 2022). Maximum temperature indicated a negative influence on the radial growth of Turkey oak under the four growing conditions in the Vas County in Hungary. This can be attributed to the higher decreasing soil moisture available to the tree root system. Also, it is typical for deciduous trees to shed some of their leaves to conserve water within trees. There is equally a halt to photosynthetic process.

Precipitation, one of the primary growth-controlling factor, had a comparable effect and but positive influence only on pure stand Turkey oak trees throughout 1961 to 2021. This can be attributed to the fact that trees in the pure stands are competing for water from the same levels within the soil. These findings partly agree with reports in other comparative studies on Turkey oak and Sessile oak (*Quercus petraea*) (Lebourgeois et al., 2004; Čufar et al., 2014; Hafner et al., 2015; Stojanović et al., 2018).

5.5 Conclusions

This study explored the effect of four growth conditions (stand composition, i.e. mixed and pure stands; and soil quality, i.e. good and poor) on the annual TRW characteristics of Turkey oak, a drought-tolerant species, in Vas County in Hungary. Additionally, this study examined the correlation of TRWs with the weather factors of precipitation and maximum temperature. The focus was on these two climate variables because of the future changing climate predictions: the increment of mean air temperature and its associated severe and frequent drought globally. This study found that mixed species planting produced trees with wider annual rings than counterparts in pure stands. The quality of soil had less influence on annual TRW. Mixed species planting with Turkey oak tree produced annual-ring width of about 2.3 mm whereas counterparts in pure species plots produced 1.7 mm. Further research is needed with larger sample size to confirm if Turkey oak should be emphatically considered for mixed-species planting.

Chapter 6. Wood tissue characteristics among Hungarian Turkey oak

6.1 Introduction

The global demand for wood will continue to grow larger despite the introduction of alternative competitive materials. Decades ago, the demand for wood was mainly attributed to the expected annual increment in human population which leads to more consumption of timber and wood products. Presently, the demand for timber in the construction industry is sustained because wood has proven to be energy efficient and provides low-carbon buildings desired for today's urban environments. Gradually, it is being understood that the use of wood could help to address some of the current climate emergencies (Sikkema et al., 2023). Currently, the traditionally known uses of wood and wood products (construction, indoor and outdoor furniture, pulp and paper products, fuelwood) are active. Meanwhile, scientific innovations have added other advanced wood utilizations such as bioethanol production and nanotechnological applications (Mishra et al., 2017; Moon et al., 2006).

Wood is a renewable biomaterial produced from a single layer of meristematic cells called the vascular cambium (Larson, 1994; Plomion et al., 2001). The functionality of the cambium is affected by factors including plant hormones, and climate/environmental variables such as temperature, precipitation, and photoperiod, especially in the temperate and Mediterranean climatic zones. Generally, wood formation is an irreversible structural growth process (Hilty et al., 2021). It is influenced by genetics, age, edaphic conditions, silvicultural practices, and prevailing climate (Plomion et al., 2001). The complex wood formation process results in the formation of a unique internal structure, amongst others, useful for diagnostic purposes.

The anatomical structure of every wood carries enormous information. It can uncover the conditions in which the tree had grown. Again, an internal structure of wood can be the base to forecast other properties of wood. For instance, fibre length and cell wall thickness influence the mechanical properties of the wood; cell wall thickness, and parenchyma content (because of the reserved photosynthate stored in them and its tendency to attract insects) can influence wood's natural durability in an outdoor application (Donaldson, 2019; Rungwattana & Hietz, 2018).

Hungary is associated with three native oak species which are Sessile oak (*Quercus petraea*), Turkey oak, and Pedunculate oak (*Quercus robur*). They are ecologically important because they thrive at different altitudes. Economically, oak forests are relevant to Hungary (Barkham & Jakucs, 1986). Turkey oak has been categorized as drought-tolerant because it could withstand annual rainfall below 400 mm and it usually develops deep and penetrating taproots (Fuchs et al., 2021; Popa et al., 2013). The aesthetic appearance of Turkey oak is like that of noble oaks, making it a good substitute. These ecological and morphological traits project Turkey oak as a potential contributor to the Hungarian wood industry in terms of raw material supply, amidst predicted climate warmings. This study focused on answering the question 'can soil quality and stand composition compromise the wood quality of Turkey oak in Vas County of Western Hungary?'. The specific objectives were to examine the effect of soil quality (poor and good) and stand composition (mixed-species and pure-species Turkey oak stands) on the anatomy of wood (xylem) tissue cells (fibre, vessel).

6.2 Materials and Methods

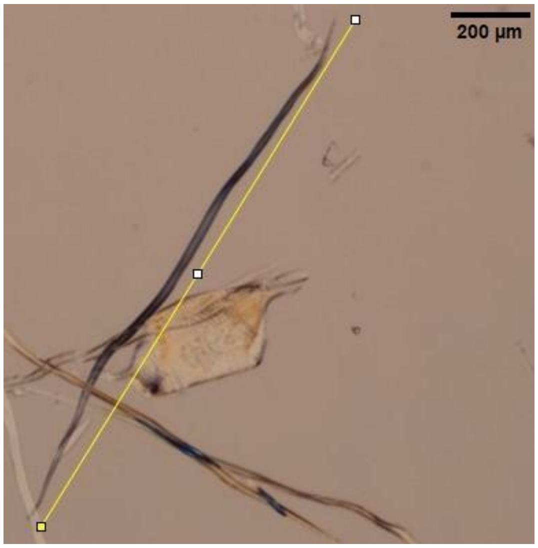
The materials have been described in Chapter 5

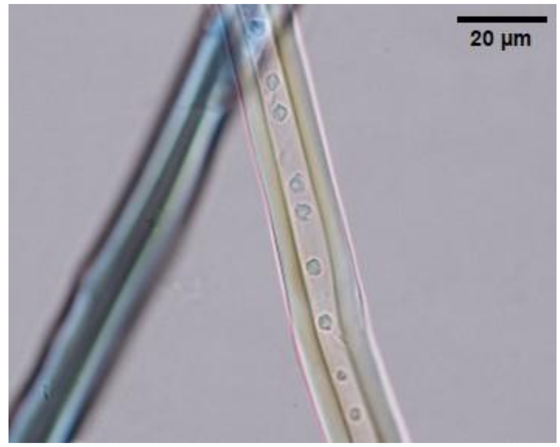
6.2.1 Determination of Wood Tissue Dimensions

Matchstick-sized wood samples were collected from both the sapwood and heartwood portions of each tree to absorb any variability within each tree. Samples were macerated (the process of disintegrating the wood into individual tissues by dissolving the lignin that binds them) using standard protocols adopted in previous studies (Govina et al., 2021; Schweingruber, 2007). The samples were kept in labelled vials containing a solution of 1:1 glacial acetic acid and hydrogen peroxide and placed in a water bath at 65 °C (Figure 19). Complete maceration was achieved after 72 hours. The macerated vials were thoroughly rinsed with distilled water and allowed to stay for 24 hours.

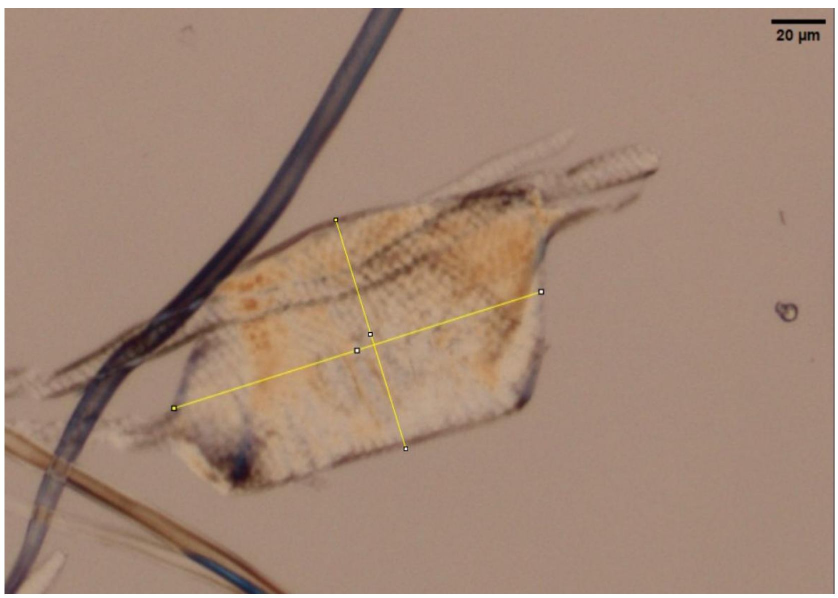
The fibres and vessels (Figure 20) were observed using an advanced microscope (Nikon Eclipse 80i, Nikon, Japan) and measured with ProScan III software (Prior Scientific Limited, United Kingdom). Only straight and unbroken fibres were measured for length, diameter, lumen diameter and double wall thickness (Figure 20). Straight and unbroken vessel elements were identified from the macerate to measure their length and diameter.

Figure 19: Memmert Water Bath





A B



C

Figure 20: Some wood tissues after maceration. Plate A is captured under x40 magnification and carries illustrations on how fibre length was measured. Plate C illustrates vessel dimensions measurement. Plates B and C were captured under x400.

6.2.2 Data analysis

The data generated in an Excel spreadsheet was organized, the mean values were calculated, and graphs were developed in Excel (version Office 365, Microsoft, United State of America) software. The statistical analyses were conducted in the R statistical programme

(R Core Team, 2021). An analysis of variance was done to determine differences between mean values. A Tukey post hoc test for significant differences at a 95% confidence level was further conducted to confirm where the significant difference emerged from.

6.3 Results

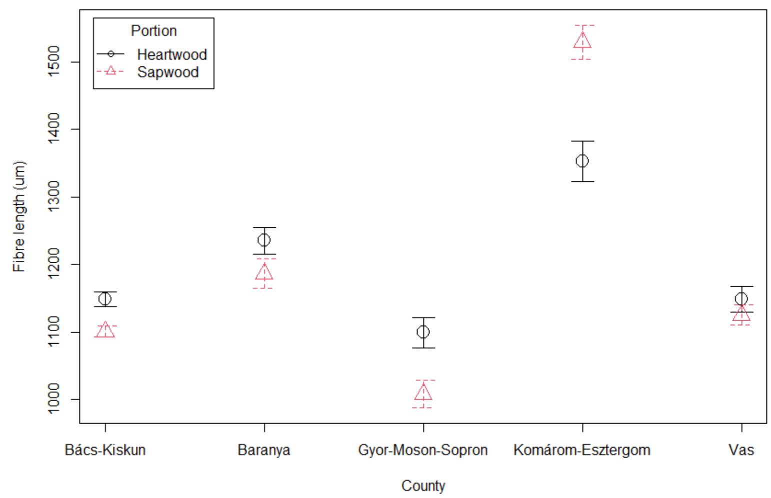
6.3.1 Fibre characteristics across counties

The mean values of fibre length observed for Turkey oak wood in this study ranged from 1065.14 to 1438.65 (μm). The sapwood portions recorded slightly lower fibre lengths, except for materials collected from the Komárom-Esztergom County (Figure 21A). The highest mean fibre length of 1529.27 was recorded from Komárom-Esztergom sapwood samples. Wood materials from the Gyor-Moson-Sopron area recorded the lowest fibre length. The differences between the mean values, at County level, are statistically significant across the Counties (Table 111).

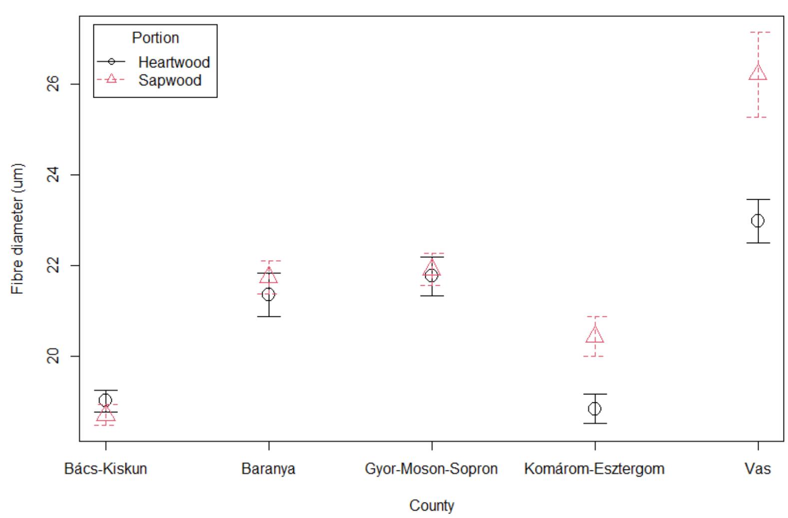
The mean fibre diameter values recorded ranged from 18.86 to 24.59 (μm). The sapwood of Turkey oak materials from the Bács-Kiskun area recorded the lowest values, whereas the sapwood of counterparts from Vas County recorded the highest value. There is no regular pattern in fibre diameter between sapwood and heartwood (Figure 21B). The differences between the mean values, at County level, are statistically significant across Counties (Table 111).

The mean values of fibre lumen diameter width ranged from 4.78 to 9.46 (μm). The lowest mean value was recorded for the sapwood of Komárom-Esztergom materials whereas the highest mean value was recorded for Heartwood of Gyor-Moson-Sopron area materials (Figure 21C). Generally, the heartwood portion had a wider lumen except for materials from the Baranya County. The differences between the mean values, at County level, are statistically significant (Table 111).

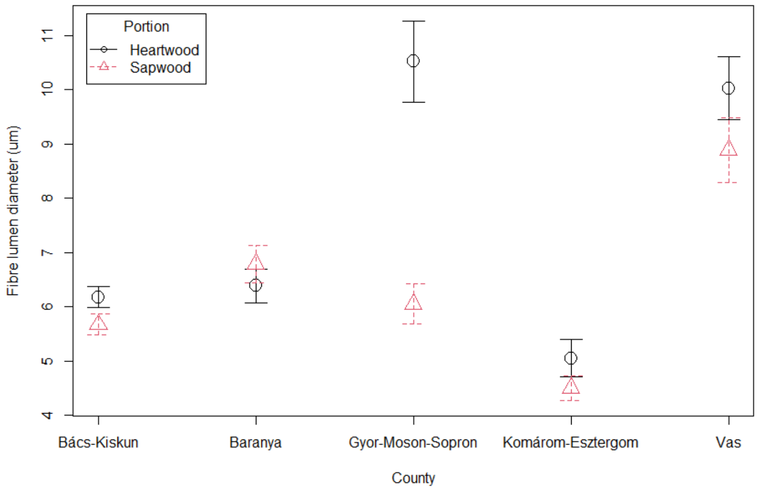
The mean values of fibre double wall thickness ranged from 12.94 to 15.13 (μm). The minimum mean value was from Gyor-Moson-Sopron heartwood materials whereas the maximum value was from the sapwood of Vas County materials (Figure 22D). Mostly, the sapwood materials had thicker walls than the heartwood materials. The differences between the mean values, at County level, are statistically significant (Table 111).


Portion
Heartwood
Sapwood
Fibre length (um)
1000
1100
1200
1300
1400
1500
Bács-Kiskun
Baranya
Gyor-Moson-Sopron
Komárom-Esztergom
Vas
County

A


Portion
Heartwood
Sapwood
Fibre diameter (um)
20
22
24
26
Bács-Kiskun
Baranya
Gyor-Moson-Sopron
Komárom-Esztergom
Vas
County

B



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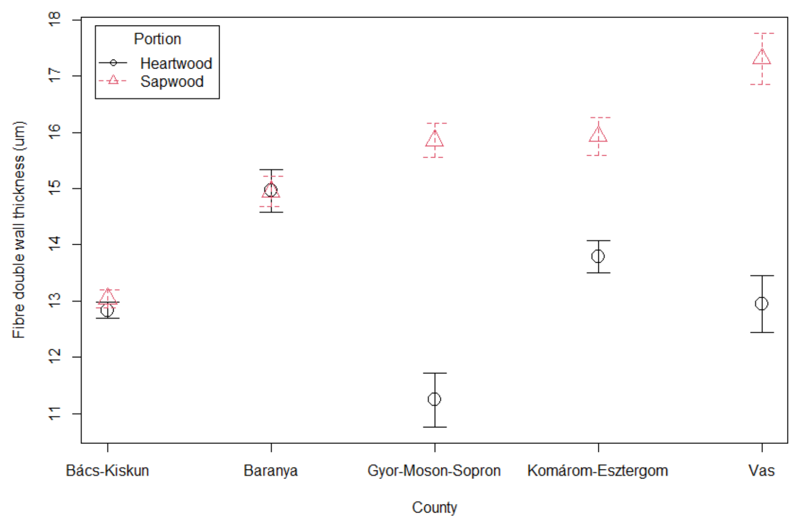


D

Figure 21: Fiber characteristics. Plate A – fibre length, Plate B – fibre diameter, Plate C – fibre lumen diameter, Plate D – fibre double wall thickness. The error bars are standard errors of the means.

Table 11: Mean values for fibre characteristics for Turkey oak wood from different Counties in Hungary. In parentheses, are the standard deviation.

Locality	***Fibre length (um)***	***Fibre diameter (um)***	***Fibre lumen diameter (um)***	***Fibre double wall thickness (um)***
Bács-Kiskun	1124.72 (165)^{a}	18.86 (2.83)^{a}	5.93 (2.40)^{a}	12.94 (1.88)^{a}
Baranya	1210.49 (228)^{b}	21.54 (3.01)^{bc}	6.59 (2.40)^{a}	14.96 (2.38)^{b}
Komárom-Esztergom	1438.65 (250)^{c}	19.63 (2.26)^{ab}	4.78 (1.61)^{a}	14.86 (2.03)^{b}
Gyor-Moson-Sopron	1065.14 (261)^{d}	21.82 (3.33)^{c}	8.76 (5.77)^{b}	13.06 (4.20)^{a}
Vas	1137.29 (254)^{a}	24.59 (7.71)^{d}	9.46 (5.97)^{b}	15.13 (5.31)^{b}
p-value	<0.05	<0.05	<0.05	<0.05

Superscript letters $^{a, b, c, d}$ represent output of Tukey post hoc test in ANOVA. Different superscripts indicate that the compared mean values are significantly different.

6.3.2 Fibre characteristics per soil quality and stand composition in Vas County

Figure 22 and Figure 23 present the mean values indicating the influence of soil quality and stand composition on fibre length and fibre double cell wall thickness, respectively. Figure 22 represents the mean values with separated heartwood and sapwood whereas Figure 23 combines same. These two traits (fibre length and double wall thickness) were under focus because of their known influence on other strength properties and consequently on timber quality and properties. Considering soil quality, the mean values for fibre length Turkey oak wood from good and poor soils were 1096.69±291 µm and 1179.59±201 µm, respectively. Fibre double cell wall thicknesses were 13.7±5.24 µm and 16.67±4.98 µm, respectively. Regarding stand composition, mean fibre length values for mixed- and pure stands were 1273.6±192 µm and 975.89±223 µm, whereas its corresponding cell wall thickness mean values were 17.29±5 µm and 12.92±4 µm, respectively. The average fibre diameter (Table 12) for the trees collected from good and poor-quality soils were 23.84±4 µm and 25.39±10 µm, whereas the fibre lumen widths were 10.14±6 µm and 8.72±6 µm, respectively. For the stand composition category of mixed and pure stands, fibre diameters were 26.92±10 µm and 22.21±3 µm whereas the fibre lumen diameter were 9.63±5 µm and 9.28±6 µm, respectively. Statistically, the influence of the soil quality was highly significant only on the fibre length and its double wall thickness as shown in Table 12. Stand composition also showed high statistical influence (p-value <0.05) on the fibre characteristics except for the lumen width.

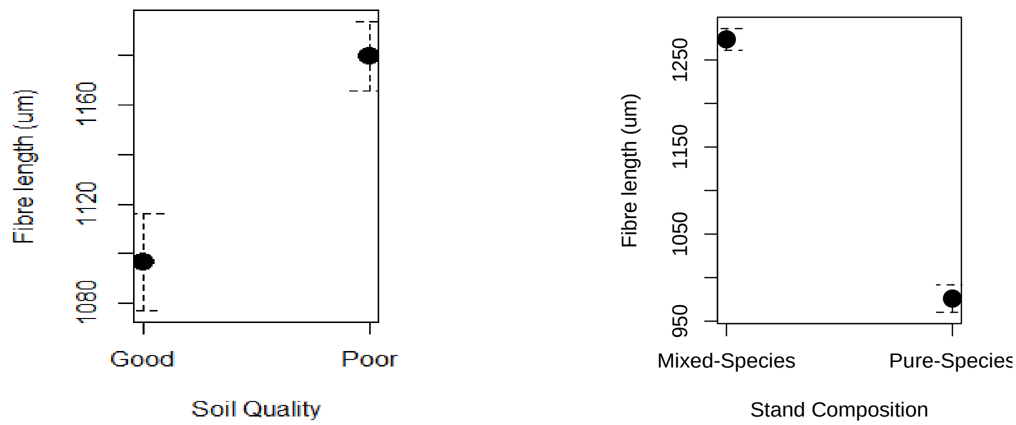


Figure 22: Mean value of fibre length for Turkey oak grown on good and poor soil, and as a pure and mixed-species stand. The error bars are standard errors of the means. This out does not differentiate heartwood and sapwood portions.

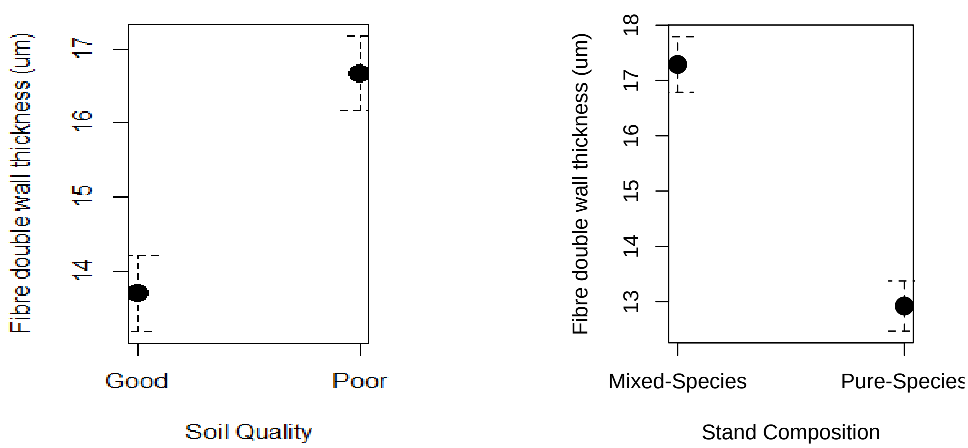


Figure 23: Mean values of fibre wall thickness for Turkey oak grown on good and poor soil, and as a mono and mixed-species stand. The error bars displayed are standard errors of the means.

Table 12: P-values derived from ANOVA and post hoc for the measured fibre characteristics

Factors	***Fibre length***	***Fibre diameter***	***Fibre lumen diameter***	***Fibre double wall thickness***
Soil quality	<0.05 ***	0.15	0.089	<0.05 ***
Stand composition	<0.05 ***	<0.05 ***	0.679	<0.05 ***
Combination of Soil quality and species composition	<0.05 ***	<0.05 ***	<0.05 ***	<0.05 ***

* – significant, ** – high significant, *** – highly significant

The effects on the combination of soil quality and stand composition are shown from Figures 25 to 28. The results indicate that Turkey oak wood from mixed stands, irrespective of soil quality produced wood with longer fibres and thicker walls (Figure 25 and 28, respectively). The poor soil produced wood with a larger fibre diameter and fibre lumen diameter. Comparatively, wood materials from pure Turkey oak stand on good soil had an intermediate fibre diameter but wider lumen width. The influence of the combination of categories under the two factors was statistically highly significant on all the fibre characteristics as shown in Table 12.

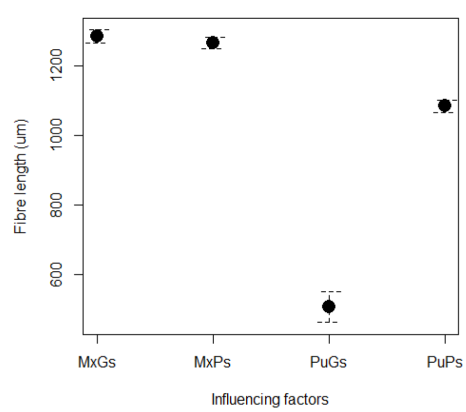


Figure 24: Mean values of fibre length for Turkey oak grown under four different conditions. The error bars display standard errors of the means.

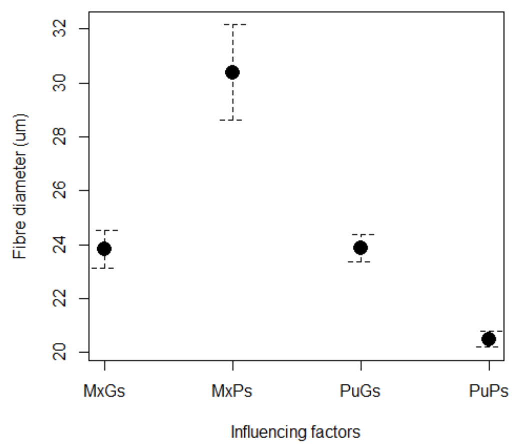


Figure 25: Mean value of fibre diameter for Turkey oak grown under four different conditions. The error bars display standard errors of the means.

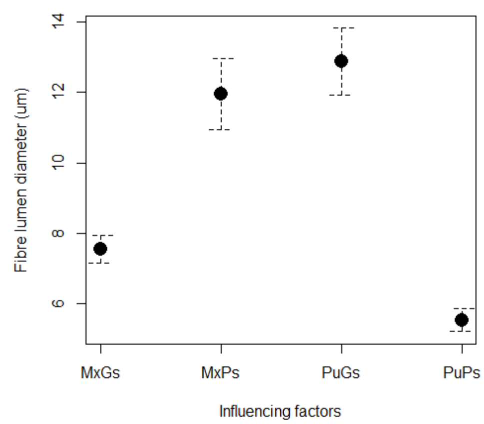


Figure 26: Mean values of fibre lumen width for Turkey oak grown under four different conditions. The error bars display standard errors of the means.

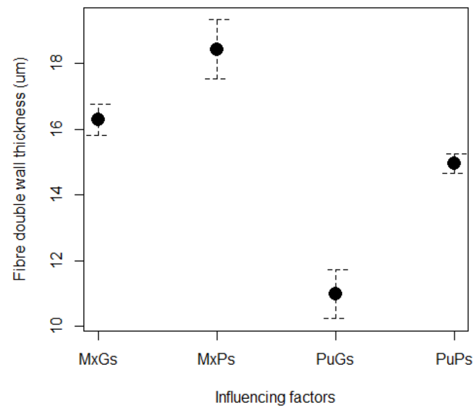


Figure 27: Mean values of fibre double wall thickness for Turkey oak grown under four different conditions. The error bars display standard errors of the means.

6.3.3 Vessel characteristics

The vessel characteristics measured were diameter and length. The findings, presented in Table 13, are comparable among the sampled Turkey oak trees. In the latewood portion, the vessel length has less variability than in vessel diameter. On good soil, the average vessel diameter was 111.44±38 µm whereas on poor soil, the average was 236.87±140 µm. In earlywood portions, average vessel length is similar to length values at latewood portion. Certainly, the vessel diameters are far larger in the earlywood part. Statistically, ANOVA proved that soil quality and stand composition had a highly significant influence on vessel characteristics in only latewood portion.

Table 13: Mean values for vessel characteristics in earlywood and latewood portion of Turkey oak grown under varied plot conditions. In parentheses are the standard deviations. LW – Latewood, EW–Earlywood.

Factor	***Category***	***LW vessel length (µm)***	***LW vessel diameter (µm)***	***EW vessel length (µm)***	***EW vessel diameter (µm)***
Soil quality	Good	503.30 (73.50)	111.44 (38.45)	416.08 (83.80)	442.31 (79.98)
	Poor	415.73 (88.03)	236.87 (139.97)	410.78 (74.33)	410.34 (65.75)
Stand composition	Mixed	488.81 (103.37)	132.85 (35.59)	362.11 (76.11)	307.31 (63.23)
	Pure	419.28 (82.59)	231.6 (145.50)	418.65 (84.98)	448.74 (75.91)

Table 14: P-values from ANOVA for the measured vessel characteristics. Abbreviation: LW – Latewood, EW – Earlywood.

Factors	***LW vessel length***	***LW vessel diameter***	***EW vessel length***	***EW vessel diameter***
Soil quality	<0.001 ***	<0.001 ***	0.651	0.091
Stand composition	<0.001 ***	<0.001 ***	0.523	0.084
Combination of Soil quality and stand composition	<0.001 ***	<0.001 ***	0.041	0.045

* – significant, ** – high significant, *** – highly significant

6.4 Discussion

6.4.1 Fibre Characteristics across study sites

The fibre biometry (length, diameter, lumen width and double wall thickness) of Turkey oak wood studied agrees with mean values reported in studies for the genus Quercus (Govina et al., 2023; Jokanović et al., 2022; Ortega-Gutiérrez et al., 2023; Todorović et al., 2022). The localities where the woods were sourced from are distinguished by the amount of precipitation received throughout the year, especially in the growing season. Gyor-Moson-Sopron and Vas Counties are western part of Hungary which receives more precipitation than the northern or southern part (Komárom-Esztergom and Bács-Kiskun). The observed differences in mean values for fibre dimensions can be attributed to genotype, edaphic conditions, silvicultural practices and climate variability (Jokanović et al., 2022). The most crucial environmental variable reported to affect the growth and development of the genus Quercus is soil moisture (Gadermaier et al., 2024; Jokanovic et al., 2019). It is reported that fibre characteristics are influenced by fluctuations in the environment variables. For instance, it is reported that fibre dimensions decrease with a reduction in available soil moisture (Arend & Fromm, 2007; De Micco et al., 2016).

6.4.2 Fibre characteristics by silviculture

Considering soil quality, trees from poor quality soils produce wood with longer fibres with corresponding thicker walls. On the other hand, trees in mixed-stand forests produced wood with significantly longer fibres, larger diameters, and thicker cell walls. The study findings agree with some reported literature; For pedunculate oak (*Quercus robur*), a study found fibre length range of 1100 – 1350 µm; diameter of 18 – 22 µm; and cell wall thickness of 10 – 14 µm (Gülsoy et al., 2005). A study on Persian oak (*Quercus brantii*) across 3 sites in Iran found fibre length in a range of 770 – 940 µm whereas fibre wall thickness ranged between 5 and 6 µm. The same study found that soil quality had a significant influence on the tissue characteristics (Dong et al., 2022). In another study on Oregon white oak (*Quercus garryana*) grown with Douglas fir, fibre length was between 1100 and 1200 µm, in which stand composition demonstrated a significant influence (Lei et al., 1996). Luostarinen and Hakkarainen (2019) also found the influence of site and soil type on fibre characteristics of *Betula pubescens*.

6.4.3 Vessel characteristics as influenced by silviculture

The capacity of trees to safely transport water along the coordinated interplay of root, stem and leaf is supported among other factors by vessel diameter. Therefore, vessels contribute to tree growth and survival (Cavender-Bares et al., 2004). Wood from pure Turkey oak stands had considerably larger vessels, irrespective of soil quality. We found that both soil quality and stand composition had significant influence on only the latewood vessel length and diameter. This finding is related to other literature. For instance, studies found earlywood vessel range of 164 – 272 (Corcuera et al., 2004; Lei et al., 1996).

On the contrary, the site was not a significant source of variation for vessel characteristics but rather the individual trees (Feuillat & Keller, 1997; Zhao et al., 2014). The finding contradicts with this present study output. The variation recorded can be attributed to the hydraulic strategies adopted by the trees per their conditions (Fontes et al., 2022). A special case is the formation of latewood, where the trees need to regulate their water transport to avoid hydraulic cavitation. Latewood had an average minimum vessel diameter as low as 46.15 µm (Table 15).

Table 15: Range of vessel characteristics for Turkey oak wood from the Vas County in Hungary.

Stand composition	Soil quality	Tree-ring portion	Length (µm)		Diameter (µm)	
			Minimum	Maximum	Minimum	Maximum
Pure-species	Good	Earlywood	285.95	566.91	278.09	301.54
		Latewood	366.05	586.42	63.57	128.93
	Poor	Earlywood	223.62	516.53	274.97	290.78
		Latewood	224.87	638.64	53.08	176.84
Mixed-species	Good	Earlywood	362.12	381.89	307.31	337.32
		Latewood	393.89	647.85	46.15	190.08
	Poor	Earlywood	314.88	344.51	345.73	398.22
		Latewood	184.57	552.76	79.52	180.16

6.5 Conclusion

Part of the expected output of Hungarian Forests Management are sustainable supply of wood for their industries and to encourage valuable utilization of lesser-used species. Turkey oak has withstood ecological conditions over the years and has provided scientific evidence to adapt to future predictions. The drought-tolerant species exist across different sites in Hungary from young to mature stands. Regarding fibre biometry, there was no clear pattern observed for the materials harvested from the five different sites across Hungary. The increasing demand for wood and wood products suggests that there should be increased effort in biomass production across all forest types. While plantation wood has almost become the backstop of the natural forest supply, efforts to establish them should be affordable.

Turkey oak is naturally capable of performing in a range of sites, even with minimum soil moisture. It can be inferred from this study that stand composition is an important factor when considering forest plantations for Turkey oak. Wood from mixed stand forests had longer, and thicker walled fibres, but not wider fibre diameters necessarily. These traits are promising for better strength properties. Stand composition is also a source of significant variation for vessel characteristics in latewood portions. The co-habitation of Turkey oak with other tree species will not only improve biodiversity and ecosystem but also the wood quality of Turkey oak. However, it might be highlighted that the genotype of the trees harvested for the study was unknown. Therefore, further studies are required to clearly establish the sources of variation for effective forest management.

Chapter 7: Wood tissue proportion in Hungarian Turkey oak.

7.1 Brief Introduction

The vascular system in woody plants is complex because it has cells of distinct structures that support diverse functions. In hardwoods, vessels and parenchyma are responsible for axial and radial movements and storage of water, minerals and food. Fibres are responsible for providing mechanical support. Physiologically, during programmed cell-death associated with wood formation, excess photosynthate stored in the parenchyma cells (starch) remains in the xylem (Déjardin et al., 2010; Evert & Eichhorn, 2006).

The accessibility to the stored starch by agents of biodegradation, such as insects, is possible for untreated wood expose during utilization. This stored starch is a weakness for wood because it affects its natural durability. Regarding tissue characteristics, studies have found their relationship with strength properties among different species (Hang et al., 2024; Naji et al., 2011). Collectively, wood tissues affect the appearance of wood and its aesthetic acceptance (Dinwoodie, 2000). Inferably, knowledge of the proportion of each wood tissue is vital for efficient utilization. It can help to better understand the wood material and therefore predict its behavior in application. This present study investigated the influence of soil quality and stand composition on tissue proportion among the Turkey oak wood materials in Vas County.

7.2 Sample preparation and experimentation

Wood samples with cross-sectional dimensions of 1 x 1 cm and 2 cm long were prepared. Four of the wood samples were taken from each disc to address any variability within. They were left in labelled vials (Figure 29) containing water for 14 days to begin wood softening for the sectioning procedure. Each piece of wood is boiled in water for about 15 minutes to enhance the softening, before sectioning. The warm sample is mounted on a sliding microtome [Epredia™ HM 430, Thermo Scientific, Göteborg, Sweden] (Figure 29) set up to cut sections between 10 and 20 µm thickness using disposable blades (Model A35, Feather Safety Razor Co. Ltd, Japan).

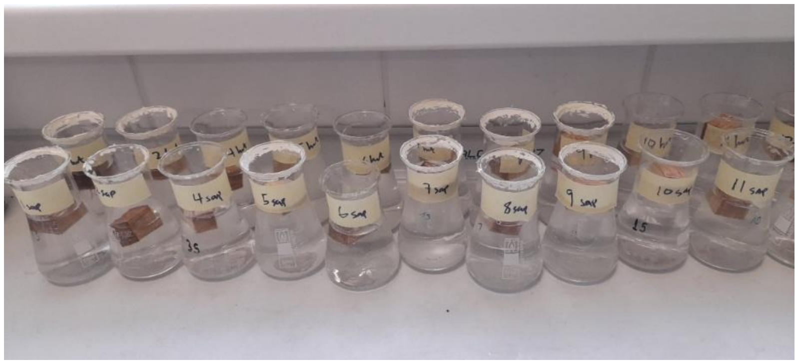


Figure 28: Wood samples soaked in labelled vials

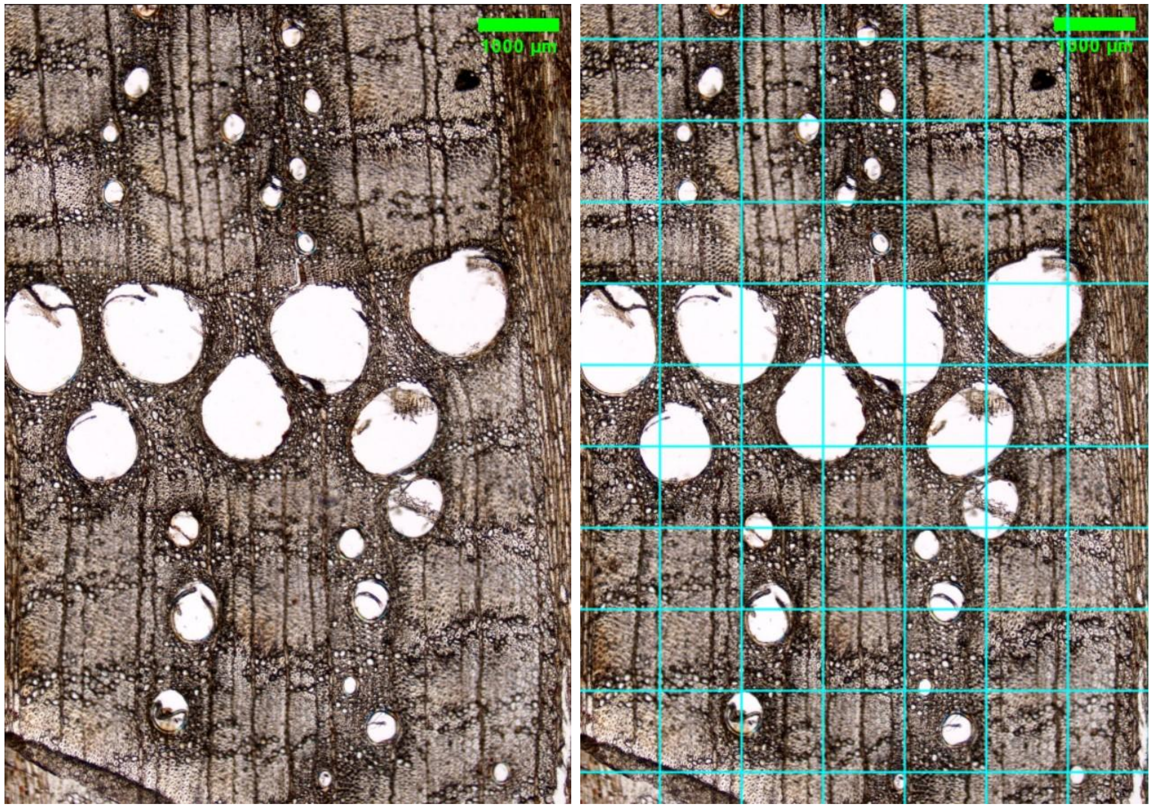
Figure 29: Sliding Microtome for wood sectioning.

Only sections for the cross-sections were generated for this study. The best sections were transferred into distilled water to clean off any residues. The cleaned sections were immediately mounted in glycerol on specimen slides and cover slips were carefully dropped on them.

7.2.1 Measurement

The prepared specimen slides were placed on the stage of an Advanced Compound Microscope (Nikon Eclipse 80i, Nikon, Japan) for imaging with x100 and x400 magnifications. The microscope is connected to a computer through a ProScan III software (Prior Scientific Limited, United Kingdom) that runs a digital camera (Figure 30). The image files had individual measurement scales to ensure accurate capture of data (Figure 31). One file is loaded at a time into the ImageJ software and the scale is manually set through the 'set scale' button.

Figure 30: Nikon Eclipse 80i, Nikon, Japan.



A B

Figure 31: Micro-sections of a transverse surface of Turkey oak wood. A is the initial image and B is the processed image (overlaying the grid) in ImageJ.

The area of each loaded image was determined. Similarly, a defined scale grid of 1 mm^2, with 20 points evenly distributed dots was superimposed, at least 5 times, per image. The placement was done diagonally to the ray direction. The tissue elements were counted per the locations of each distributed dot. The average counts of the dots were calculated as a percentage of the 20 dots. Axial parenchyma and ray were not jointly counted.

The data generated was organized and partly analyzed in Microsoft Excel spreadsheet software (version Office 365, Microsoft, United States of America). Further analyses were conducted in the R statistical package (R Core Team, 2021). An analysis of variance was done to differences between mean values. Tukey post hoc test at 95% confidence level was further conducted to confirm where the significant difference emerged from.

7.3 Results

The mean proportion of wood (xylem) cells are reported in Table 16. The proportion of vessels was greater in woods from pure stands of Turkey oak. The mean values ranged from 40 – 44% (Table 16). The same materials had mean parenchyma proportion between 16 – 18%, and fibres from 39 – 43%. Wood materials from mixed-species planted Turkey oak expressed mean vessel proportions ranging from 32 – 34%, parenchyma proportions between 20 – 22% and fibre from 44 – 47%. Generally, there were differences observed between mean values for tissue proportion within heartwood and sapwood. But mean values for fibre proportion for material grown in mixed and on good soils remained the same (46%). Again, wood samples from the pure stands of Turkey oak grown on poor soil also had identical mean parenchyma proportions of 16%. Statistically with ANOVA, both soil quality and stand composition had significant influence on the mean tissue proportions for Turkey oak ($p<0.05$).

Table 16: Mean values for tissue proportion in Turkey oak wood grown in different plots in Vas County. In parentheses are the standard deviation.

Influencing Factor	***Radial Portion***	***Vessels (%)***	***Parenchyma (%)***	***Fibres (%)***
MxGs (Bögöte)	Heartwood	32 (5)^{a}	22 (4)^{a}	46 (9)^{a}
	Sapwood	33 (4)^{a}	21 (3)^{a}	46 (8)^{a}
MxPs (Egyházasrádóc)	Heartwood	33 (6)^{a}	20 (4)^{b}	47 (10)^{a}
	Sapwood	34 (7)^{a}	22 (4)^{a}	44 (8)^{b}
PuGs (Hosszúpereszteg)	Heartwood	44 (9)^{b}	17 (5)^{c}	39 (7)^{b}
	Sapwood	40 (8)^{b}	18 (3)^{b}	42 (8)^{c}
PuPs (Vasvár)	Heartwood	41 (8)^{c}	16 (4)^{c}	43 (8)^{c}
	Sapwood	43 (9)^{c}	16 (3)^{b}	42 (6)^{c}

Superscript letters $^{a, b, c, d}$ represent output of Tukey post hoc test in ANOVA. Different superscripts indicate that the compared mean values are significantly different.

7.4 Discussion

The study finding agrees with work done in the United States on *Quercus garryana* (Oregon white oak) and *Quercus faginea* (Lei et al., 1996; Sousa et al., 2014). The proportion of fibres, the cells responsible for mechanical support, was more in the wood of Turkey oak that grew among other wood species. In one breath, this could mean that their strength properties are superior to counterparts from pure Turkey oak plantations. On the other hand, the same materials from mixed-stands also have higher proportion parenchyma cells.

Potentially, this could also suggest that the natural durability of the same material could be easily reduced than the other counterparts in this study. However, regarding the living trees, Turkey oak in mixed stands would have more tendency to defend themselves when necessary. In terms of wood's attractive appearance, parenchyma has an influence (Dinwoodie, 2000). Hence, variation in parenchyma among materials may influence how the Turkey oak materials appeal to wood users. There was no definite pattern regarding the cells proportion between heartwood and sapwood.

7.5 Conclusion

The study suggests that planting Turkey oak in mixed-stands could produce wood materials with a higher proportion of fibres. Regarding living trees, more fibres are useful for tree stability against factors such as wind. Regarding wood utilization, more fibres in Turkey oak is desirable because the characteristic of fibre, such as length and wall thickness, influence other strength properties. Referring to parenchyma cells proportion, live Turkey oak trees could benefit from numerous parenchyma cells. On the contrary, the same wood materials in utilization could be more susceptible to biodeterioration agents seeking to attack the photosynthate stored in the numerous parenchyma cells.

Chapter 8. Basic density and selected mechanical properties

8.1 Introduction

The relationship between wood density and mechanical properties, whether inferred through modelling or directly determined, among many species has been studies (Kiaei, 2013; Zhang, 1997). Bending strength can be described as the maximum endurance force that a wood can withstand under a gradually applied load. The bending elastic modulus presents knowledge about how rigid or the elasticity of a wood. Modulus of Elasticity (MoE), technically known as Young's Modulus, protects the wood's inherent ability to recover from deformation when the stress is removed. Generally, a higher value of bending elastic modulus for wood means that the wood exhibits more plasticity. During the bending test, the maximum load a sample can carry before destruction is known as the Modulus of Rupture (MoR). Compressive strength can be measured on all the 3 principal planes of wood (longitudinal, radial and tangential). However, the common compressive strength is determined parallel to the grain. It is an important mechanical property that indicates the level at which a wood can withstand a load along the grain direction.

In construction engineering, a key strength indicator (indicative of load-bearing capacity) is inferred from the overall strength property of wood, which is also calculated by summing bending strength and compressive strength parallel to the grain. Hardness is another important strength property of wood. It represents how wood can resist any form of indentation. This variable is measured by the force required to embed half-portion of a ball of 11.28 mm diameter. Regarding wood quality, a standard evaluation requires a determination of the quality coefficient of the wood. This is simply a ratio of mechanical strength and basic density (Kretschmann, 2010). Wood density is an important trait that is usually associated with wood quality. This report covers wood density, modulus of elasticity, modulus of rupture, compression and hardness for Turkey oak grown in both mixed-species and pure-species stands.

8.2 Materials and Methods

They study site and tree sampling have been described in chapter 3, section 3.3.

8.2.1 Sample preparations

Wood logs of about 50 cm long were cut from the breast height point of each tree. The logs were processed into boards and staked in a dryer to reduce their moisture amount.

The desired moisture content (about 12-16%), which could facilitate sample processing, was reached after 6 weeks. Clear and straight-grain samples were prepared from the boards according to standards for respective mechanical property tests.

Density

The determination of wood basic density was based on the oven-dry method. Following the standard DIN 68364 and ISO-13061-02 (2017), the test wood samples were conditioned for one week at controlled temperature and humidity (20 ± 1°C; 65 ± 5%). Afterwards, the samples were weighed on an electronic balance. The dimensions of each wood sample were measured using an electronic caliper (Figure 32). The samples were left in an oven at 103 °C, and their weight was monitored every 24 hours until a constant weight was reached. The wood density was calculated based on weight and volume. Moisture content (MC) was also calculated based on ISO-13061 – 01 (2017). The following formulae were used for MC and density.

- Moisture content, MC (%) = (Moist weight - Dry weight)/ Dry weight *100
- Density, ρ (g/cm^3) = Weight (g) / Volume (cm^3)

A

B

Figure 32: Towards density determination. Plate A – Weighing and dimensional measurement. Plate B – Samples in an Oven.

Mechanical tests

The various tests were conducted with specimens stored under normal climate conditions of Temperature 20°C, and relative humidity of 65% until equilibrium moisture was reached. The wood samples stored were ready after reaching constant weight. The strength tests were performed using the Instron 4208 universal material tester (Norwood, USA) and Charpy impact tester (Leominster, England) (Figures 34-36). The following equations were adopted to determine the selected mechanical properties in this study.

- Bending strength (Modulus of Rupture) = $3FL/2RT^2$
  where:
  L : 240mm (interval between the 2 support points).
  F : maximum load.

- Modulus of elasticity: $Ew = FL^3/4RT^3D_v$
  where:
  F : Load difference
  L : interval between the 2 support points
  R : width
  T : thickness
  D_v : variation of deflection.

- Compression strength: $\sigma = Fmax/(R * T)$
  where:
  F_{max} is the maximum load in N
  R and T are the actual cross-dimensions of test piece.

- Janka Hardness: $HJ = Fmax/100mm2$
  where:
  F is the maximum load during penetration.

Table 17: Wood property, sample dimension, testing standard used.

Test	***Variable***	***Dimensions (mm)***	***Test standard followed***	***Minimum number of samples per group***
Physical	Moisture content	20x20x30	ISO 13061-01 (2017)	36
	Basic density	20x20x30	ISO 13061-02 (2017)	36
Mechanical	Modulus of rupture	20x20x300	ISO 13061-03 (2017)	36
	Modulus of elasticity	20x20x300	ISO 13061-04 (2017)	36
	Compressive strength	20x20x30	ISO 13061-17 (2017)	36
	Hardness (Janka)	50x50x50	ISO 13061-12 (2017)	12

Modulus of rupture and modulus of elasticity

Figure 33: Prepared wood samples and Instron UTM for modulus of rupture and modulus of elasticity.

Compression strength

Figure 34: Typical outlook of compressed Turkey oak wood sample.

Hardness

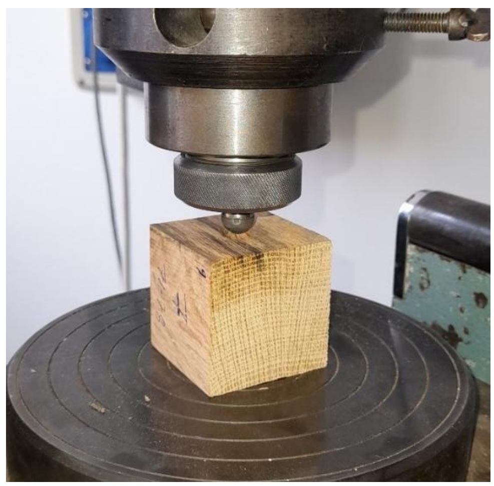


Figure 35: An illustration of wood hardness testing.

The data generated for density and mechanical properties were organized and partly analyzed in Microsoft Excel spreadsheet software (version Office 365, Microsoft, United States of America). Graphical representations were conducted in both Excel spreadsheet and R statistical package R (R Core Team, 2021). An analysis of variance (ANOVA) for the means was conducted to test statistical significance of the differences between mean values. Tukey post hoc test at 95% confidence level was employed to show where the significant difference emerged from.

8.3 Results

The basic density values for the entire study samples ranged from 0.65 to 0.87 g/cm^3. The mean values for the various plots are presented in (Table 18). The wood materials mixed stands exhibited higher basic density. Also, the wood materials from good-quality soils expressed greater variability as observed with the gap between heartwood and sapwood values. Also, the heartwood portion recorded higher mean values of basic density. (Figure 36). The highest mean value for basic density was recorded for wood materials from mixed-species stand on good-quality soil. The lowest mean basic density value was recorded for materials from pure stand grown on good soil (Figure 36). Stand compositing had significant influence on basic density, unlike soil quality ($p<0.05$).

The bending modulus of elasticity (MoE) for study samples ranged from 8929 to 15954 (MPa). The mean values for the respective plots are presented in Table 18. The highest mean values were recorded for the materials from mixed-species stands. The dispersal of data within tree was low among the plots except for pure stand plot on a good-quality soil (Figure 37). Analysis of variance (ANOVA) on the mean values suggests that both stand composition and soil quality had a statistically significant influence on the bending modulus of elasticity ($p<0.05$).

The bending strength (MoR) values for the study wood materials ranged from 104.04 to 167.89 MPa. The mean values for the plots are in Table 18. The pattern of mean value between the plots is like what has been reported for basic density and bending modulus of elasticity. However, the sapwoods exhibited higher mean values for the plots except for pure stand grown on good-quality soil. The mean values of bending strength for Turkey oak wood properties from mixed-species stand grown on good soils materials are higher (Figure 38). Again, the statistical analysis with ANOVA indicates that stand composition and soil quality had significant influence on MoR.

The compression strength parallel to the grain ranged from 49.55 to 70.08 MPa, and the mean values for the plots are found in Table 18. This variable was comparatively equally distributed between the wood materials groups (Figure 39). There was no statistically significant difference between their mean values of compression strength for Turkey oak grown in Vas County.

The Janka hardness_longitudinal ranged between 77.15 to 106.71 N/mm^2. The mean values for all three principal surfaces of wood are presented in Table 19. Janka hardness_radial ranged between 63.22 to 88.26 N/mm^2, whereas tangential ranged between 64.43 to 93.10 N/mm^2. Stand composition had significant influence on Janka hardness tested on all principal surfaces.

Table 18: Mean values of basic density, modulus of elasticity, modulus of rupture and compression strength properties for Turkey oak grown in mixed and pure-species stand in Vas County of Hungary.

Influencing factors	***Basic density (g/cm^3)***	***Modulus of elasticity (MPa)***	***Modulus of Rupture (MPa)***	***Compressing strength (MPa)***
MxGs	0.76 (0.05)^a	14060.62 (849.28)^a	145.86 (10.24)^a	62.88 (4.01)^a
MxPs	0.74 (0.02)^a	12697.69 (620.28)^b	131.44 (9.47)^b	63.11 (3.85)^a
PuGs	0.72 (0.04)^b	11289.66 (997.61)^c	119.02 (7.39)^c	62.88 (3.87)^a
PuPs	0.72 (0.02)^b	12148.23 (1069.85)^d	131.36 (11.92)^b	62.31 (3.43)^a

Superscript letters $^{a, b, c, d}$ represent output of Tukey post hoc test in ANOVA. Different superscripts indicate that the compared mean values are significantly different.

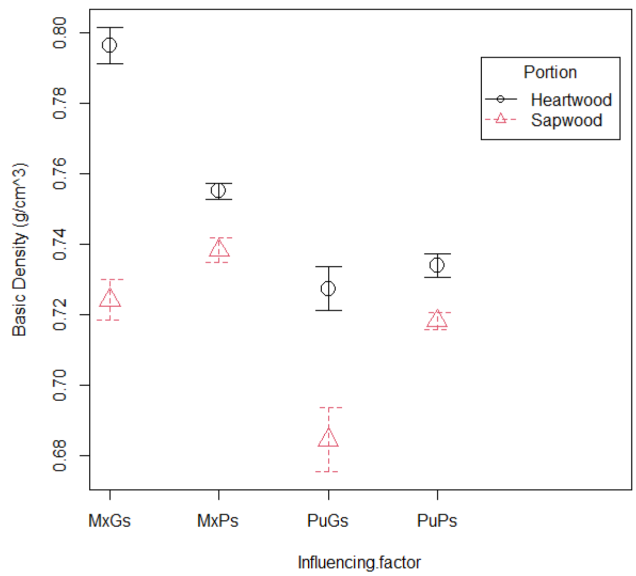


Figure 36: Basic density for Turkey oak from mixed and pure-species stand in Vas County of Hungary.

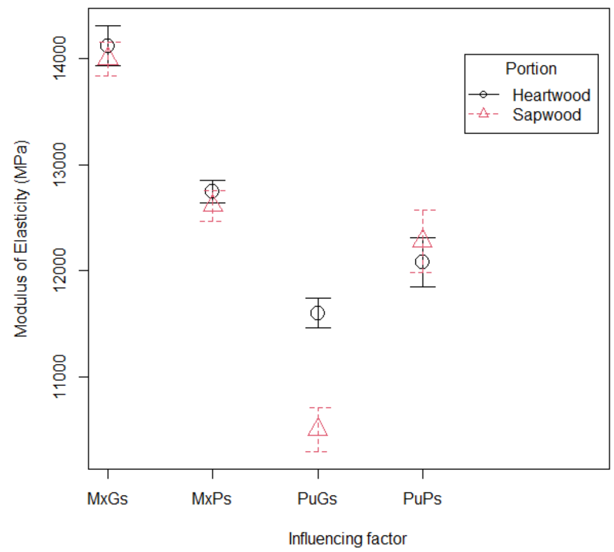


Figure 37: Modulus of elasticity for Turkey oak from mixed and pure-species stand in Vas County of Hungary.

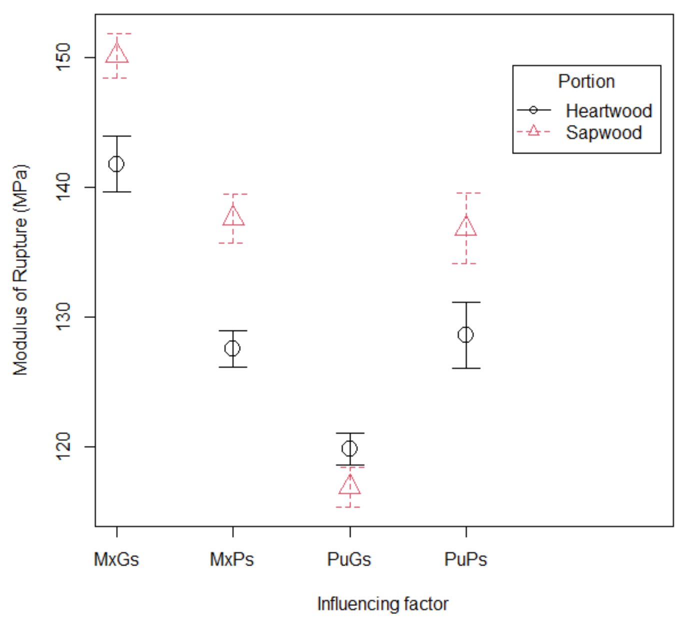


Figure 38: Modulus of rupture for Turkey oak from mixed and pure-species stand in Vas County of Hungary.

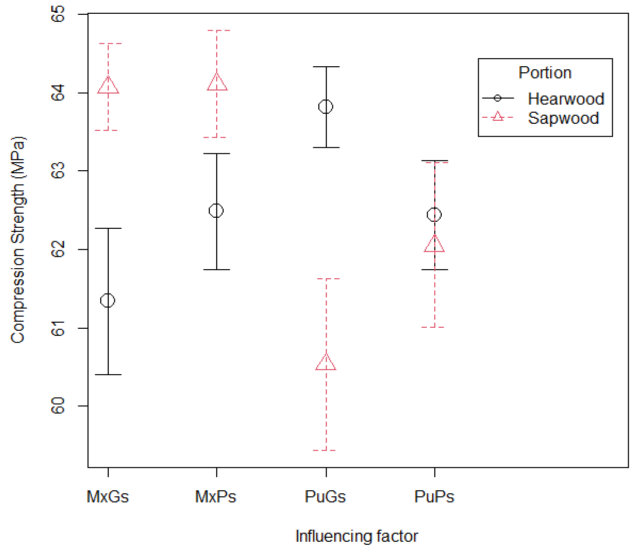


Figure 39: Compression strength across of Turkey oak from mixed and pure species stand in Vas County of Hungary.

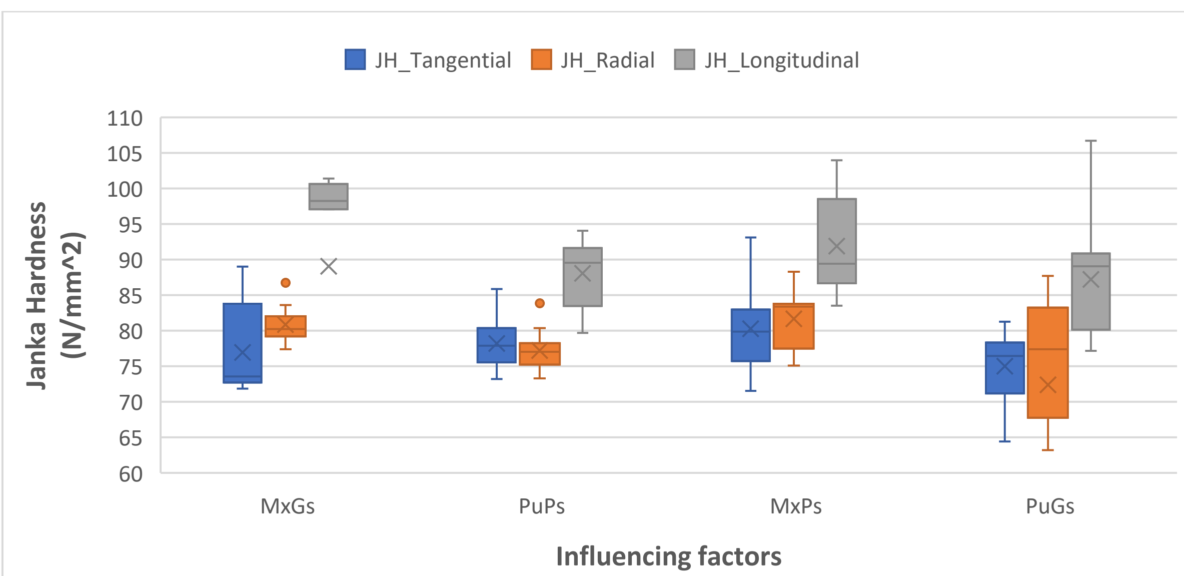


Figure 40: Boxplot of Janka hardness along the principal surfaces of wood for Turkey oak from mixed and pure species stand in Vas County of Hungary.

Table 19: Mean values of Janka hardness in three principal surface of Turkey oak wood grown under influence of stand composition and soil quality.

Influencing factor	***JH_Longitudinal***	***JH_Radial***	***JH_Tangential***
MxGs	98.92 (1.74)^{a}	80.84 (2.68)^{ab}	76.92 (6.20)^{ab}
MxPs	91.88 (6.93)^{b}	81.66 (3.99)^{a}	80.28 (5.70)^{a}
PuGs	87.18 (7.39)^{b}	76.65 (7.64)^{b}	74.98 (4.76)^{b}
PuPs	88.07 (4.44)^{b}	77.19 (2.63)^{ab}	78.21 (3.46)^{ab}

Superscript letters $^{a, b, c, d}$ represent output of Tukey post hoc test in ANOVA. Different superscripts indicate that the compared mean values are significantly different.

8.4 Discussion

The basic density values reported were comparable to each other. The mean values found in this study agree with other studies on red oak species. A study on *Quercus garryana* in the United States reported a basic density value of 0.83 g/cm^3 (Lei et al., 1996). In a Romanian study, Deaconu et al. (2023b) reported a basic density of 0.75 g/cm3 for Turkey oak. In Portugal, the basic density range of 0.91 – 1.04 g/cm3 was determined for *Quercus faginea* (Sousa et al., 2018). The mean values of basic density range of 0.78 – 0.83 g/cm^3 has been reported for Turkey oak in Kosovo (Bajraktari et al., 2018b). *Quercus brantii* exhibited basic density range between 0.73 – 0.83 g/cm^3 whereas *Q. rubra* had a mean value of 0.74 g/cm^3 (Nazari et al., 2020; Todorović et al., 2022). In Slovenia, a study on *Q. petraea*, *Q. robur*, and *Q. cerris*, basic density ranged between 0.60 – 0.79 g/cm^3 (Merela & Čufar, 2013). The low values in the Slovenian study were for the white oaks (*Q. petraea*, *Q. robur*). Regarding the significant effect of stand composition on the basic density of Quercus, this study agrees with work reported in the literature (Monaco et al., 2011; Pretzsch & Schütze, 2021). Krajnc et al. (2021), found same effect on *Quercus pubescens*.

The mean values of bending modulus of elasticity (MoE) found in this study for Turkey oak agree with findings reported *Quercus faginea* in Portugal with values ranging from 7323.8 – 11,700.6 MPa (Knapic et al., 2022). On the same variable, Merela & Čufar (2013) reported of MoE range between 8000 – 13500 MPa. The bending strength values found in this study also agree with values (89.7 – 119.7 MPa; 85 -120 MPa) reported by Knapic et al., (2022) and Merela & Čufar (2013). Regarding compression strength parallel to the grain, the same Portuguese and Slovenian research studies w with values ranging from 42 – 54 MPa and 42 – 57 MPa respectively, i.e. relevant to this study.

The range values for longitudinal and radial hardness found by Merela & Čufar (2013) are 38 – 40 MPa and 18 – 20 MPa respectively. Bajraktari et al. (2018b) found a hardness mean value of 39.9 MPa. This present study found similar values for hardness. Generally, the overall strength properties found in this study suggests that neither stand composition nor site quality could produce inferior quality of Turkey oak wood. The values found are within the required standard values for domestic flooring applications or commercial uses with moderate traffic (EN14354, 2004).

8.5 Conclusion

The Turkey oak wood materials for the studies exhibited basic density and strength properties within reasonable agreement with other Turkey oaks from other territories besides Hungary. Additionally, the study findings are similar to values reported in the literature for other species in the same genus. This study found that the wood materials from mixed species stands recorded significant higher mean values in both basic density and selected strength properties. Compression strength was not significantly influenced by either stand composition or soil quality.

Chapter 9. Research Summary

Climate experts are pointing to research evidence that suggests the future climate will be harsher. According to them, there will be an increase in temperature, prolonged severe drought, and irregular rainfall patterns. Ecophysiologists in Europe and Hungary have classified Turkey oak, a temperate hardwood species, to be a drought-tolerant tree species. The same wood species is industrially a lesser-used species in Hungary though it could exhibit some characteristics that are closely compared to other noble oaks. Concerning the present climate prediction, Turkey oak seem to be a promising species for future forestation programs. The hardwood species can survive and accordingly produce biomass to support the Hungarian wood industry in addressing the increasing demand for wood and wood products. This research investigated the effects of site (good and bad soil quality) and stand composition (pure and mixed species) on fundamental wood tissues of Turkey oak in Hungary. The study found answers to whether these influencing factors could compromise the properties of Turkey oak wood in Hungary.

The heartwood-sapwood portion for all Turkey oak discs was distinct, with the heartwoods being darker brown than the sapwood. Turkey oak tree from Szombathely had the highest mean heartwood proportions of 75% followed by the wood materials from the Baranya County area with 71%. Turkey oak wood from the Pilis and Kecskemet area had the highest mean sapwood proportion of 40%. Overall, soil quality had a statistically significant influence on the heartwood-sapwood proportions. Soil quality and stand composition, had no statistically significant influence on heartwood-sapwood proportion. However, the combination of these factors had a slight statistically significant effect on heartwood-sapwood proportion.

The mean annual tree-ring width ranged from 1.32 to 3.68 (mm). Generally, the annual rings were wider at the juvenile portions, followed by the heartwood and then the sapwood. On the contrary, wood materials from the Komárom-Esztergom area had an irregular pattern of wider heartwood annual rings. The Juvenile portion of the Baranya materials recorded the widest mean annual ring width (3.68 mm). A wider mean annual ring width for heartwood was recorded for the Komárom-Esztergom materials and also for sapwood. As a ring-porous species, the vessels variation and arrangement were conspicuous. Soil quality had little significance on the ring width at both the juvenile and sapwood portions. Stand composition had little statistical significance on only the tree-ring width in the heartwood portion. Overall, the mean tree-ring width for Turkey oak trees from mixed-species stands was larger than trees from pure Turkey oak stands. Similarly, the earlywood and latewood widths within yearly tree-rings were larger for Turkey oak trees from mixed species planting.

The tree ring width (TRW) correlated with maximum temperature and precipitation has generated the following outcomes for the analyzed period 1961 to 2021. There was a positive correlation between precipitation and TRW. The correlations for wood from the four different plots were weak to moderate (co-efficient = 0.09 – 0.32) within the individual growing sites. Contrary, the correlation between maximum temperature and TRW is negative. This means that an increase in maximum temperature will result in a decrease in ring width. Across the four plots, the negative correlations were moderate (co-efficient = -0.32 to -0.42).

The mean values of fibre length observed for Turkey oak wood in this study ranged from 1065.14 to 1529.27 (μm). The sapwood portions recorded slightly lower fibre lengths, except for materials collected from Komárom-Esztergom. The highest mean fibre length of 1529.27 (μm) was recorded for sapwood from Komárom-Esztergom. Wood materials from the Gyor-Moson-Sopron area recorded the lowest fibre length. The mean values of fibre double cell wall thickness ranged from 12.94 to 15.13 (μm). The minimum mean value was from Gyor-Moson-Sopron heartwood materials whereas the maximum value was from the sapwood of trees from Vas County. Mostly, the sapwood materials had thicker cell walls than the heartwood materials. Considering soil quality, the mean values for fibre length Turkey oak wood from good and poor soil were 1096.69±291 μm and 1179.59±201 μm, respectively. Fibre double cell wall thicknesses were 13.7±5.24 μm and 16.67±4.98 μm, respectively. Regarding stand composition, fibre length for mixed- and pure-species planting were 1273.6±192 μm and 975.89±223 μm, whereas its corresponding cell double wall thickness values were 17.29±5 μm and 12.92±4 μm, respectively. The results indicate that Turkey oak wood from mixed stands, irrespective of soil quality produced wood with longer fibres and thicker walls. On good soil, the average vessel diameter was 111.44±38 μm whereas on poor soil the average was 236.87±140 μm. Vessel length was similar in both earlywood and latewood portions. Certainly, the vessel diameters are far wider in the earlywood part.

The proportion of vessels was greater in wood from pure stands of Turkey oak. The mean values for vessel proportion ranged from 40 – 44%. The same materials had a mean parenchyma proportion between 16 – 18%, and the fibre proportion was from 39 – 43%. Wood materials from mixed-species planted Turkey oak expressed mean vessel proportions ranging from 32 – 34%, parenchyma proportions between 20 – 22% and fibre from 44 – 47%. Generally, there were differences observed between mean values for tissue proportion within heartwood and sapwood. But mean values for fibre proportion for material grown in mixed and on good soils remained the same (46%). Again, wood samples from the pure stands of Turkey oak grown on poor soil also had same mean parenchyma proportion of 16%.

Basic density values ranged from 0.65 to 0.87 g/cm^3. The wood materials from the Turkey oak trees grown in combination with other hardwood species (mixed stands) exhibited higher basic density. Also, the wood materials from good-quality soils expressed greater variability. The bending modulus of elasticity (MoE) for study samples ranged from 8929 to 15954 (MPa). Significantly higher means values were recorded for the materials from mixed species stands. The bending strength (MoR) for the studied wood materials ranged from 104.04 to 167.89 (MPa). The trend for mean values was like that of basic density and MoE, just that radially the sapwood recorded higher mean MoR value. The compression strength parallel to the grain ranged from 49.55 to 70.08 MPa. Stand composition and soil quality had significant influence on basic density, MoE, and MoR of the Turkey oak materials. Janka hardness of longitudinal surface ranged between 77.15 to 106.71 N/mm^2; radial surface ranged between 63.22 to 88.26 N/mm^2 and on tangential surface ranged between 64.43 to 93.10 N/mm^2. Stand composition had a moderate influence on Janka hardness determined for all principal surfaces of the Turkey oak wood from plots in the Vas County of Hungary. Turkey oak wood grown in Hungary can be considered for valuable utilization.

Novel findings

This dissertation outlines novel findings related to six thematic areas of wood science. The findings have been disseminated in journal articles, conference papers, and posters. The findings are listed below.

Thesis 1. Heartwood-sapwood proportion

I concluded that Turkey oak trees grown in Hungary has at least 71% of heartwood. The higher heartwood proportions are recorded for trees grown at moist sites in Western Hungary like Sopron. I proved that the higher sapwood proportion is recorded for trees in the dryer sites like Pilis and Kecskemet.

Thesis 2. Annual tree-ring width characteristics

I found that the annual tree-ring width for Turkey oak in Vas, Gyor-Moson-Sopron, Baranya, Bács-Kiskun, and Komárom-Esztergom Counties in Hungary ranged from 1.32 – 3.68 mm. I also found that Turkey oak trees planted in a mixture with other hardwood species produced the widest annual tree-ring width. Also, Turkey oak grown in western Hungary, areas noted to have higher precipitation, produced wider annual tree-rings. It is also concluded that soil quality and stand composition, did not influence annual tree-ring width. However, a combination of these two factors has influenced annual tree-rings.

Thesis 3. Annual tree-ring related to climate variable

Correlation analyses displayed that there is a weak to moderate positive correlation (co-efficient = 0.09 – 0.32) between annual tree-ring width and precipitation. This implies that an increase in maximum precipitation will result in a wider annual tree-ring. It is also proved that there is moderate negative correlation (co-efficient = -0.32 to -0.42) between annual tree-ring width and maximum temperature. This implies that an increment in maximum temperature will cause the production of narrower annual tree-rings.

Thesis 4. Wood tissue characteristics (fibers and vessels morphology)

The mean values reported for tissue characteristics for Turkey oak wood across sites in Hungary conform with the reported literature. I found that poor soils produced Turkey oak wood with longer and thicker wall fibres. I also proved that wood materials from Turkey oak planted in mixed-species stands produced fibres with longer and thicker walls. I found that soil quality and stand composition was a major influencer of vessel length and diameter in the latewood portion of tree-rings of Turkey oak.

Thesis 5. Wood/Xylem Tissue proportion

I found that Turkey oak planted in pure stand composition produced wood with higher proportion of vessels. I also proved that Turkey oak in mixed stand composition produced wood with more fibres proportion per 1 mm^2. It is also concluded that soil quality has an influence on tissue proportion among Turkey oak wood in Hungary.

Thesis 6. Mechanical properties

In general wood specimens from Turkey oak trees grown in mixed-species stands have higher basic wood density, bending modulus of elasticity (MOE), bending strength (MOR) and Janka hardness on the longitudinal surface. This resonates with the earlier proof that mixed-species planted Turkey oak wood materials have longer fibres and thicker cell walls. Overall, I found that planting Turkey oak in mixed-species stands may warrant the development of wood with better mechanical properties that are fundamental for efficient utilization. In regards, Turkey oak grown in Hungary is recommended for valuable utilization such as floorings, furniture, cabinets structural construction.

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