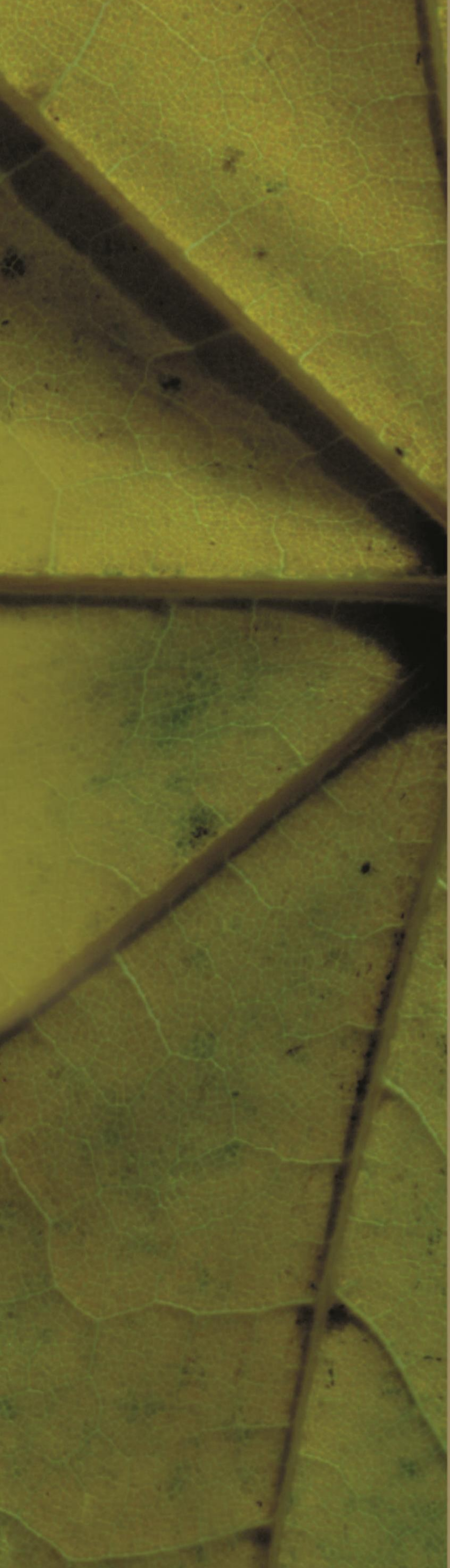

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Colour Modification of Wood by Dry Thermal Treatment between 90 ºC and 200 ºC

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Abstract – The colour modification effect of dry thermal treatment was studied in black locust (*Robinia pseudoacacia* L.), poplar (*Populus x euramericana cv. Pannonia*), Scots pine (*Pinus sylvestris* L.), spruce (*Picea abies* Mill.) and larch (*Larix decidua* L.) species in the temperature range 90-200 °C. Colour data were presented and evaluated in the CIE L*a*b* coordinate system. All thermal treatments applied altered the wood colour throughout the entire cross section regardless of the treatment temperature. At lower temperatures, wood extractives played a decisive role in colour change. The degradation products of hemicelluloses were the major determinant of the change in lightness at 200°C. Redness change in percentage showed much greater alteration than the yellowness and the lightness change. Spruce presented the greatest chromaticity coordinate (a* and b*) alteration among the investigated species. Changes in redness and yellowness followed the Arrhenius law during the investigated dry thermal treatments confirming that the temperature dependence of these colour parameters is exponential for wood material.

Arrhenius law / extractives / hemicelluloses / chroma

Kivonat – A faanyag színének változása száraz hőkezelés hatására 90 ºC és 200 ºC között. Száraz körülmények között végrehajtott termikus kezelés színváltoztató hatását vizsgáltuk akác (*Robinia pseudoacacia* L.), nyár (*Populus x euramericana cv. Pannonia*), erdei fenyő (*Pinus sylvestris* L.), lucfenyő (*Picea abies* Mill) és vörösfenyő (*Larix decidua* L.) faanyag esetében 90 – 200 °C hőmérséklet tartományban. A szín adatokat a CIE L*a*b* koordináta rendszerben adtuk meg és értékeltük. Az alkalmazott hőkezelések a faanyag színét, függetlenül az alkalmazott hőmérséklettől, a próbatestek teljes keresztmetszetében megváltoztatták. Alacsony hőmérsékleten az extrakt anyagtartalom volt meghatározó a színváltozásban. A hemicellulózok degradációs termékei határozták meg döntő mértékben a világosság változását 200 °C-on. A százalékosan megadott vörös színezetváltozás sokkal nagyobb mértékű volt, mint a sárga színezet és a világosság változása. A luc faanyaga mutatta a legnagyobb színezeti koordináta-változást (a*és b*) a vizsgált faanyagok közül. A vörös és a sárga színezet változása követte az Arrhenius törvényt a száraz termikus kezelések során mutatva, hogy ezeknek a paramétereknek a hőmérséklet függése exponenciális faanyag esetében.

Arrhenius törvény / extrahálható anyagok / hemicellulózok / színezett dússág

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1 INTRODUCTION

Extractives are the thermally most sensitive molecules in wood. Among the main chemical components, hemicelluloses are the most susceptible and can undergo thermal degradation above 100 °C. The colour modifying effect of thermal treatment is highly temperature dependent. Colour change is a slow process below 100 °C under dry conditions. Therefore, dry thermal treatment is not of industrial interest below 100 °C, but is of theoretical importance. The colour change of wooden surfaces at room temperature is an extremely slow process. Nevertheless, an indoor wooden structure will darken within a few years, even in total darkness, due to thermal degradation.

The colour modifying effect of dry thermal treatment below 150 °C is a scarcely investigated phenomenon because of the long treatment time required. Tolvaj – Faix (1996) compared the colour modification effect of thermal treatment at 90 °C under dry and wet (steaming) conditions. The treatment period was 36 days because of the slow changes under dry conditions. The results showed that the dry treatment resulted in a much smaller colour alteration compared to the wet (steam) treatment. Chen et al. (2012) studied the colour change of black locust flour caused by thermal treatment in oxygen and nitrogen atmospheric dry and wet conditions. Results showed that the samples suffered greater colour change in terms of all colour parameters (L*, a*, b*) in the presence of oxygen than in nitrogen atmosphere during dry thermal treatment at 120 °C. The decrease in lightness value was, for example, twofold in the presence of oxygen. Popescu et al. (2013) studied the chemical modifications of lime (*Tilia cordata* Mill.) wood during heat treatment at low temperature (about 140 °C) and 10% relative humidity, by infrared spectroscopy. The treatment resulted in the formation of acetic acid, which catalyse the hydrolysis reactions of hemicelluloses and amorphous cellulose. The cleavage of the β-*O*-4 linkages and splitting of the aliphatic methoxyl chains from the aromatic lignin ring was also observed.

Higher temperatures (above 150 °C) produce rapid colour change. These treatments have industrial importance not only for the quick and intensive colour change but because of some positive property change of wood. The industrially used temperature interval is 160-260 °C. Stamm – Hansen (1937) heated wood with different gases and reported the decrease of equilibrium moisture content, swelling and shrinkage values. During the next almost 100 years plenty of papers reported more and more results regarding dry thermal treatments at high temperatures. A review paper (Esteves – Pereira 2009) summarised the results of 160 papers. Also, there are several patented processes to produce thermally treated wood material. The most successful in Europe is the ThermoWood patented by Viitaniemi et al. (1997).

There are two distinct groups of thermal treatments based on the presence of oxygen. One group of treatments is where the heating medium contains oxygen while procedures in the other group exclude oxygen. Chemical reactions are quite different within these two groups since the presence of oxygen allows oxidation. Heat treatments create free radicals which can then react with oxygen forming oxidation products such as quinines (Bekhta – Niemz 2003). Such oxidative reactions are inherently impossible in the absence of oxygen. The most common option to exclude oxygen is the application of oils as heating medium. A review article (Lee et al. 2018) presents 139 papers dealing with the thermal treatment of wood in vegetable oils.

Most of the experiments in the literature were carried out in the presence of oxygen above 160 °C (Bekhta – Niemz 2003, Nuopponen et al. 2003, Sundqvist et al. 2006, Windeisen et al. 2007, Kaciková et al. 2013, Kamperidou et al. 2013, Zanuncio et al. 2015, Miklecic – Jirous-Rajkovic 2016, Griebeler et al. 2018, Sikora et al. 2018, Lo Monaco et al. 2020).

The aim of this study was to give wide insight on the temperature dependence of the colour modification effects of dry thermal treatment applying broad temperature range between 90 and 200 °C.

2 MATERIALS AND METHODS

The colour modification effect of dry thermal treatment was studied applying wide range of temperatures (90 - 200 °C) in a drying chamber. Duration of the heat-up period to reach the desired treatment temperature was 10, 15, 15, 20 and 30 minutes at 90, 110, 130, 160 and 200 °C, respectively. There was no cooling time. Samples were removed from the chamber right after finishing the treatment. Test samples for the different temperatures were cut from the same board to minimize the effect of inhomogeneity. The sample size was 100 x 20 x 10 (mm^3) having planed surfaces. Deciduous and conifer species with different extractive content were involved in the test to determine the temperature dependence of dry thermal treatment.

Black locust heartwood (*Robinia pseudoacacia* L.) was chosen because of its high extractive content. On the contrary, Poplar (*Populus x euramericana cv. Pannonia*) was tested due to its low extractive content. Larch heartwood (*Larix decidua* L.), Scots pine heartwood (*Pinus sylvestris* L.) and spruce (*Picea abies* Mill.) were chosen because of their high, medium and low extractive content, respectively. Previous results showed that the colour change generated by thermal treatment is highly temperature dependent. Longer treatment times are required at lower temperatures. Below 150 °C, several days are necessary to obtain a substantial colour change. The treatment time above this temperature limit is rather short, some hours are enough to induce remarkable colour change. That is why the treatments were caried out in two different series. In the first series (at 90, 110 and 130 °C) the chosen treatment period was 18 days. In contrast, only 6-hour treatment was applied in the second series at all investigated temperatures (at 90, 110, 130, 160 and 200 °C). Temperatures less than 90 °C generates extremely slow colour change. Therefore, this temperature value was chosen as the lower limit.

Colour parameters were measured on the radial surface of the samples to determine the average colour of earlywood and latewood. Colour measurement was carried out with a Konica-Minolta 2600d colorimeter. The CIE L* (Lightness), a* (Redness), b* (Yellowness) colour space data were calculated based on the D65 illuminant and 10° standard observer with the aperture diameter of 8 mm.

The intensity of a thermally activated process increases usually exponentially by rising temperature according to the Arrhenius law. The Arrhenius equation relates the rate of a chemical reaction k to temperature T and it includes the activation energy. The equation is simple if the activation energy is constant. The Arrhenius equation can be given in the logarithmic form:

$$\ln k = \frac{-E_a}{R}\frac{1}{T} + \ln A \tag{1}$$

Where:

R :	the universal gas constant
A:	the pre-exponential constant
k:	kinetic constant
T:	temperature
E_a	activation energy

An Arrhenius plot displays the logarithm of a kinetic constant (k, ordinate) plotted against inverse temperature (1/T, abscissa). Arrhenius plots are often used to analyse the effect of temperature on the rates of chemical reactions. For a single rate-limited thermally activated process, an Arrhenius plot gives a straight line and presents that the temperature dependence is exponential.

3 RESULTS AND DISCUSSION

This study discusses solely the colour change aspects of thermal treatments. One of the main advantages of dry thermal treatment is that it alters wood colour in its whole cross section without using any harmful chemicals. This thermal process can also be applied to modify the colour of wood species having unattractive or highly inhomogeneous initial colour. Moreover, thermally modified dark wood may substitute tropical wood species as well (Banadics et al. 2016).

Plotting the L*, a* and b* colour coordinates as a function of the treatment time could provide detailed information regarding the colour alteration. *Figure 1* shows the lightness alterations of certain investigated wood species. Dry thermal treatment at 90 °C generated almost no lightness decrease except for black locust where the total lightness decrease was 10 units at the 18th day of the treatment. Elevated temperatures amplified the lightness decreases. The investigated conifer species presented similar lightness decreases. Trendlines belonging to the same treatment temperature run close to parallel. Only spruce presented a little deviation as its lightness decrease was less intensive during the first 3 days of the treatment compared to the other two conifers. Poplar samples showed somewhat different lightness decrease character that the other species. All tree trendlines of poplar are close to straight lines and the measured lightness values generated by 90 and 110 °C are close to each other showing very little lightness decrease. In contrast, the treatment at 130 °C produced intensive lightness decrease. Poplar has low extractive content. Consequently, the darkening of the samples was generated mainly by the degradation products of hemicelluloses. 130 °C is high enough to degrade wood hemicelluloses. The missing intensive change at the beginning of the treatment procedure is due to the low extractive content of poplar and the same is valid partly for spruce as well. Black locust showed the most rapid lightness decrease during the first 3 days of treatment at all temperatures compared to the other investigated species. It is not surprising because black locust has the highest extractive content among the investigated species. Results show that the extractives are the most sensitive chemical components in wood during thermal treatment at low temperatures, followed by the hemicelluloses.

When investigating colour change procedures, a* and b* colour coordinates provide more detailed information than L* alone thus allow more subtle conclusions because the calculation of a* and b* use both X and Z tristimulus values beside Y. (Calculation of L* incorporates Y only.) Furthermore, it is important to know that the calculation of Y encompasses the reflection values of almost the whole visible wavelength interval. In contrast, determination of X utilizes two wavelength intervals around 600 and 450 nm, and the calculation of Z utilizes only one narrower wavelength interval around 450 nm. These properties of a* and b* show that they are more sensitive to the wavelength dependence of the reflectance changes than L*.

Figure 2 presents the redness change of the investigated species generated by dry thermal treatment. The initial redness values of the investigated species were for poplar, spruce, black locust, Scots pine and larch 2.7, 4.5, 5.9, 6.4 and 11.6, respectively. This order represents the extractive content values responsible for the redness of the species. Initial redness value of larch was more than twice as high as the initial a* values of the other species. The unequalled high durability of larch is lying in its special extractives responsible also for its high redness value. Gierlinger et al. (2004) investigated different larch species having large distribution of a* values (between 5.6 and 9) and found that the redness values were strongly correlated with phenolics content.

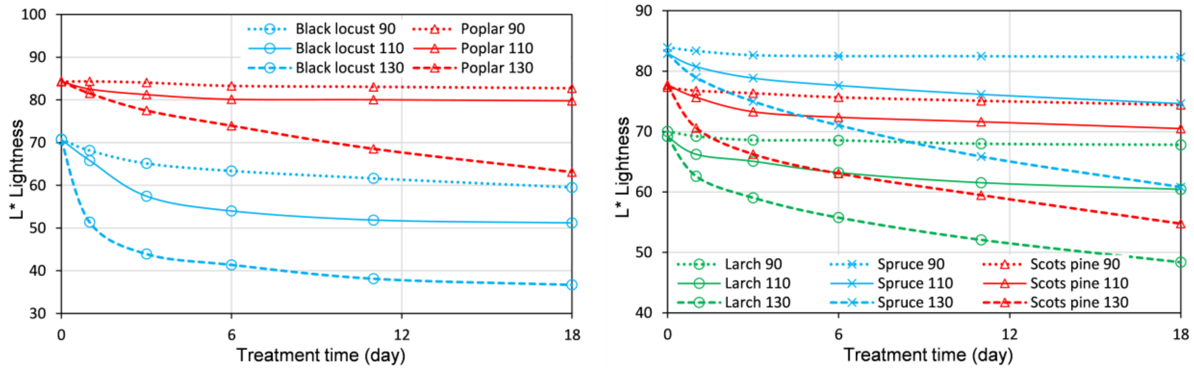

Figure 1. Lightness change of black locust, poplar, larch, spruce and Scots pine samples during dry thermal treatment

Heating at 90°C caused only a little redness increase during the 18-day treatment. There were two exceptions. The redness value of larch did not change at all while black locust produced considerable redness value increase (59 %) even at this temperature. Extractives in black locust responsible for redness increase are highly sensitive to thermal treatment. Treatment at 130 °C showed that the heat generated degradation products of extractives are chemically not stable enough. These degradation products underwent secondary degradation and reduced the redness values after 6-day treatment of black locust and after 11-day treatment of larch. Larch seems to be the thermally most stable species among the investigated ones. It has the highest initial redness value (12 units) and the maximum of redness increase was only 24 %. Spruce and Scots pine produced similar redness alterations. The redness change course of poplar was completely different to the other species. The intensive increase during the first 3 days of treatment (comparing to the whole change) was completely missing, the trendlines were close to linear. The redness increase was slow at 90 and 110 °C while at 130 °C a quite intensive and enormously high (323 %) increase could be observed during the 18-day treatment. Similar data for spruce, Scots pine, black locust and larch are 161, 106, 73 and 21 %, respectively. The results show that the degradation of hemicelluloses was dominant at 130 °C and it generated the main portion of redness increase. It seems that the extractive content could partly protect the hemicelluloses against thermal degradation. Black locust and larch with the highest extractive content showed the smallest red hue increase while poplar featuring the smallest extractive content produced the greatest red hue increase. In terms of protective effect, the type of the extractives can also play an important role. These assumptions need further chemical investigations.

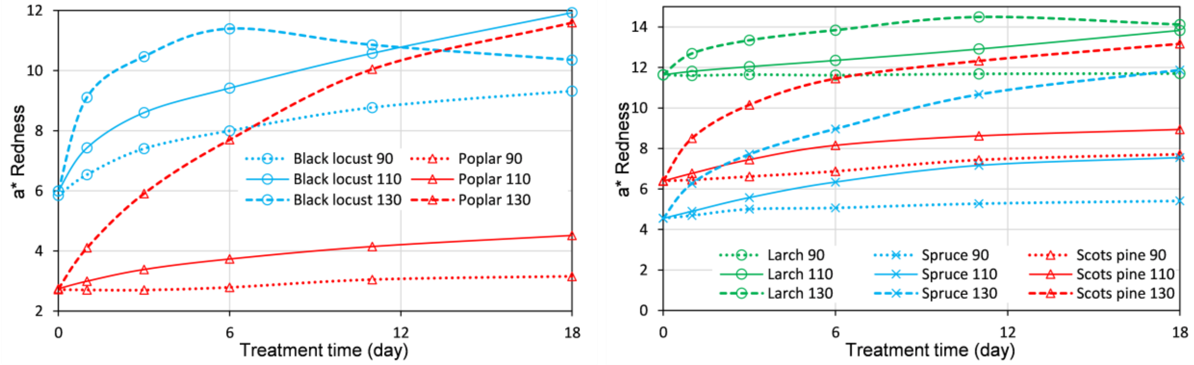

Figure 2. Redness change of black locust, poplar, larch, spruce and Scots pine samples during dry thermal treatment

Figure 3 shows the yellowness change of the investigated species induced by different dry thermal treatments. The initial values of the b* co-ordinate were 17.4, 22.3, 26.6, 27.7 and 28.1 for poplar, spruce, larch, black locust and Scots pine, respectively. The initial yellowness values were higher than the initial redness values, and the dispersion of the colour co-ordinates was smaller for yellowness than for redness. Most of species showed yellowness increase due to the thermal treatments. The only exception was black locust. Its yellowness decreased during the applied thermal treatments. The high robinetin content of black locust (covering 2-5 % of its total mass) causes its unattractive yellow colour. The robinetin type extractives are highly sensitive to thermal treatment. Heat induced degradation of these extractives led to a reduce in the yellowness of black locust even at 90 °C and caused an extremely rapid decrease during the first day already at 130 °C.

The investigated species have two types of extractives that are responsible for yellow colour. One of them generated yellowness increases while the other type produced yellowness decrease during thermal treatment. The second type of extractives were found in black locust and in larch. Larch samples produced mainly yellowness decrease at 130 °C similarly to black locust. The final yellowness value at the end of the 130 °C treatment was considerably smaller than the initial one meaning that substantial part of the decrease was induced by the degradation of extractives being originally in larch wood. Treatment at 90 °C generated slow but continuous yellowness change in all investigated species. These changes were relatively fast during the first 3 days of all treatments, then the shift slowed down afterward showing that extractives were involved in the degradation processes of all species. Treatment at 110 °C resulted in considerably greater redness change than that at 90 °C. Conifers produced both yellowness increase and decrease during the treatment at 130 °C. Maximum b* values were reached on the 11th, 6th and 1st day of the treatment of spruce, Scots pine and larch, respectively. This phenomenon shows that the heat generated degradation products underwent secondary degradation at 130 °C.

Poplar and spruce (having the smallest extractive content) presented the greatest yellowness increase on the 11th day of the treatment. These increases were 73 and 42 % for poplar and spruce at 130 °C. These data show that hemicelluloses play an important role in the yellowness change during dry thermal treatment.

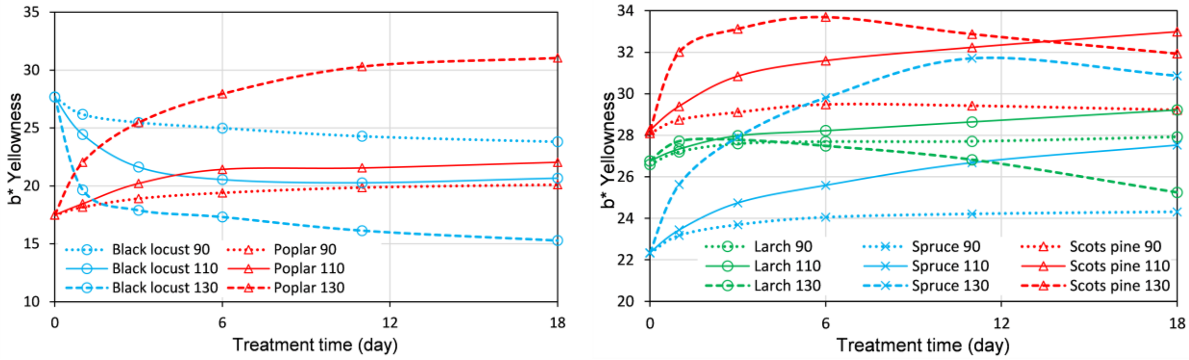

Figure 3. Yellowness change of black locust, poplar, larch, spruce and Scots pine samples during dry thermal treatment

Figure 4 present the locations of colour dots of black locust, poplar, larch, spruce and Scots pine species generated by dry treatments at 90, 110 and 130 °C. The left end of the trendlines represents the colour dots of untreated samples followed by the dots of treated samples with increasing treatment time. These figures show the change of hue and of chroma. Black locust is a great exception. It suffered great hue value decrease from 78° to 55° at 130 °C changing the greyish-yellow colour to brown tint. The treatment at 90 °C also caused considerable hue value decrease for black locust comparing to the other species. The other species hardly changed their hue at this temperature. Treatment at 110 °C produced moderate chroma increase and small hue decrease. Exception was the hue decrease of black locust. This decrease was 18 units. The chroma values (distance between the colour dot and the origin of the coordinate system) of black locust slightly increased by dry thermal treatment only. The behaviour of larch was partly exceptional as well. It showed small chroma increase and moderate hue value decrease. The other species (poplar, spruce and Scots pine) produced great chroma increase and moderate hue value decrease. The maximum chroma increase of poplar and spruce were 16 and 12 units generated by thermal treatment at 130 °C.

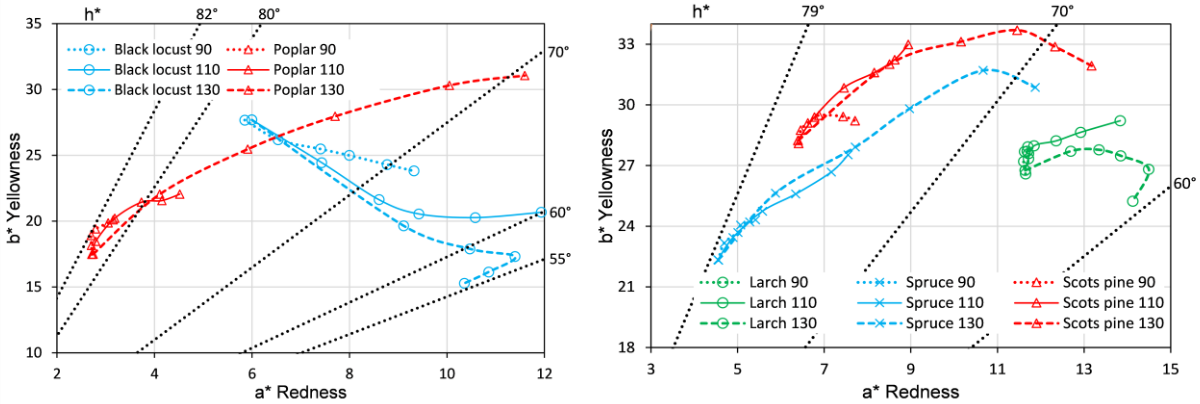

Figure 4. Colour dots of black locust, poplar, larch, spruce and Scots pine samples on the a-b* plane during dry thermal treatment. (Dots at the left end of the lines represent the untreated samples.) Constant hue (h*) lines are also indicated*

The investigated temperature range (90-130 °C) has only theoretical importance because of the long treatment time. The results show that dry thermal treatment below 100 °C causes extremely slow colour alteration. Similar results were found by Liu et al. (2016) at 100°C under semidry conditions (air RH=55 %).

Higher temperatures (above 150 °C) produce rapid colour change. These treatments have industrial importance not only for the quick and intensive colour change but because of some positive property change of wood. These temperatures generate intensive colour change after some hours of treatment already. Consequently, the treatments for the parallel investigation at 90, 130, 160 and 200 °C required short periods. The chosen time interval was 6 hours.

The lightness change data generated by the chosen four temperatures are presented in *Figure 5*. Lightness values decreased for all investigated species at all treatment temperatures. The decrease at 90°C was negligible (almost zero) for all species during the 6-hour treatment. At this temperature, the greatest lightness decrease was produced by black locust (0.7 unit). The next temperature stage, the treatment at 130 °C induced a relatively large lightness decrease (14 units) for black locust. In contrast, this data was only 0.2 unit for poplar. The elevated temperature (160 °C) doubled the lightness change of black locust compared to the effect of 130 °C. The same lightness decrease was 3, 6, 7 and 54-fold for Scots pine, spruce, larch and poplar, respectively. Comparing the behaviour of black locust and poplar, a highly different nature of changes can be observed. The dominant change of back locust was induced by its extractives. On the contrary, poplar hardly has extractives, thus its darkening was mainly generated by the degradation products of hemicelluloses. It is also visible that the degradation of extractives is rapid at the beginning of the treatment while the tendency of change is moderate later on. In contrast, the degradation progress of hemicelluloses is much more uniform during thermal treatment. Dry thermal treatment at 200 °C generated almost the same lightness decrease for all investigated species showing that the degradation of hemicelluloses is the dominant alteration at this high temperature. Black locust presented the greatest relative lightness decrease at 200 °C compared to the initial value (82 %). Researchers demonstrated that most of the extractives disappeared during thermal treatment at such high temperatures. The thermal stability of extractives in Scots pine was studied by Nuopponen et al. (2003). It was found that fats and waxes were not detectable in the sapwood edges above 160 °C. At temperatures above 200 °C all resin acids disappeared from the wood.

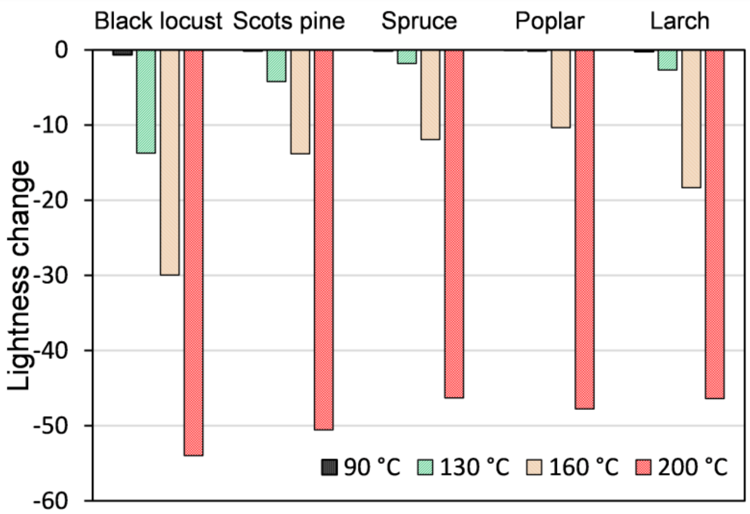

Figure 5. Lightness change of different wood species generated by 6-hour dry thermal treatment at different temperatures

Figure 6 shows the redness change of the species generated by 6-hour dry thermal treatment at various temperatures. The 6-hour treatment caused very little redness change at 90 °C. Only larch presented a slight redness decrease. It is important to mention that the redness of larch remained intact during 18-day treatment at 90 °C (see *Figure 2*). Larch showed very little redness increase at 130 °C as well. Black locust suffered the greatest redness increase at all applied temperatures except 200 °C because of the high thermal sensitivity of its extractives. The 6-hour treatment at 200 °C was too long for black locust. Its redness value started decreasing after 4-hour treatment. The other species showed small redness increase at 130 °C and medium increase at 160 °C. The only exception was poplar. Its redness increase was only 1.2 units at 160°C. These results confirm that the degradation of hemicelluloses is a relatively slow but continuous process. In contrast, the degradation of extractives is rapid at the beginning of thermal treatment and slows down afterward. Obviously, 6 hours at 160 °C was too short to induce such a strong modification of hemicelluloses that would be able to lead to a considerable redness increase. However, this short period was enough for the alteration of extractives to generate considerable redness increase in the other investigated species (except poplar). The treatment at 200°C produced great redness increase for all species. The rate of the redness change was more species dependent than in the case of lightness change. Spruce presented the greatest relative redness increase at 200 °C compared to the initial value (306 %).

Figure 7 shows the yellowness change of the species generated by 6-hour dry thermal treatment at various temperatures. Black locust is an exception in terms of yellowness change as well; b* colour coordinate of all investigated species increased except that of black locust. Although, the yellowness decreases of black locust showed similar temperature dependence than that of the other species but in the opposite direction.

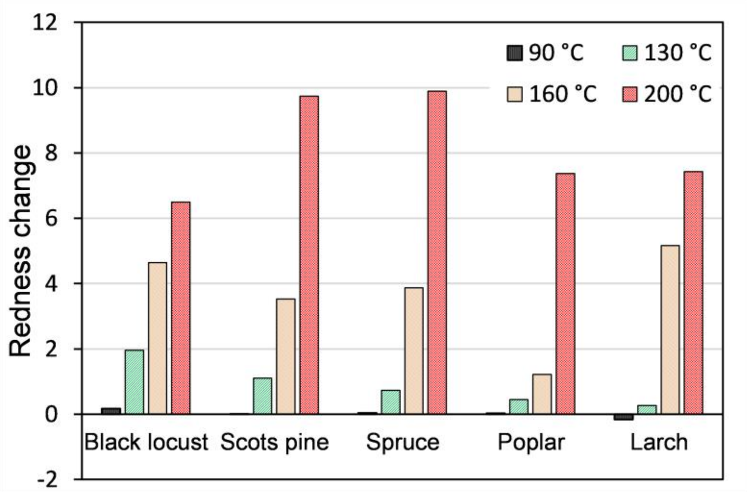

Figure 6. Redness change of different wood species generated by 6-hour dry thermal treatment at different temperatures

This behaviour can be interpreted by the high robinetin type extractive content of black locust. These extractives are responsible for the greyish-yellow initial colour of black locust. Robinetin type extractives are highly sensitive to thermal degradation and this degradation reduces the yellowness value considerably. The effect of the treatment at 90 °C seems to be neglectable in terms of b* shift similarly to the redness change, for all species. Yellowness change at high temperatures (above 130 °C) was highly species dependent. This phenomenon shows the complexity of the yellowness change. Redistribution and degradation of lignin may cause yellowness change beside the degradation of extractives and hemicelluloses. This kind of lignin related, high temperature induced processes were published in many papers (Tjeerdsma et al. 1998, Wikberg – Maunu 2004, Boonstra – Tjeerdsma 2006, Esteves – Pereira 2009, Kaciková et al. 2013, Esteves et al. 2013, Sikora et al. 2018). As it was introduced in *Figure 6*, spruce and Scots pine presented similar redness change at all temperatures. Yellowness change of these species was also similar except at 200°C. Spruce produced the greatest yellowness increase at 200 °C, which was 80 % compared to the initial value. This value was almost twice as high as the yellowness increases of Scots pine. This huge difference was probably generated by the different degradation properties of lignin within these species.

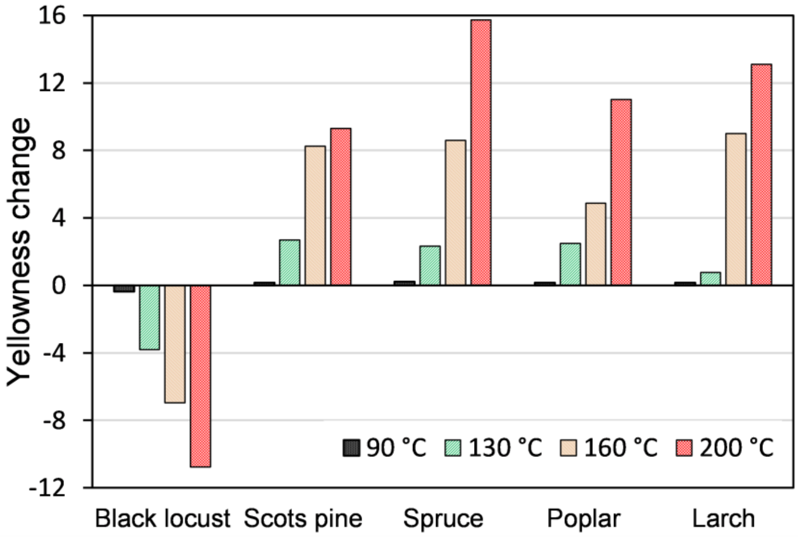

Figure 7. Yellowness change of different wood species generated by 6-hour dry thermal treatment at different temperatures

Figures 8 and 9 present the Arrhenius plots of redness and yellowness values of black locust, poplar, larch, spruce and Scots pine species thermally treated for 6 hours at different temperatures. The Arrhenius law declares that if the Arrhenius plot is a straight line, the temperature dependence of the studied process is exponential. In our case, all Arrhenius plots are straight lines presenting that both redness and yellowness changes are exponential functions of the dry thermal treatment temperature. The coefficients of determination values are quite high for all investigated wood species. R^2 values are above 0.9 for redness and above 0.92 for yellowness. The slope of the trendline for yellowness of black locust is opposite of that of the other lines showing that the changing tendency is also opposite in this case. Some colour dots are relatively fare from the trendline. The reason is laying in the colour inhomogeneity of wood. It is important to mention that all presented dots in the figures belong to different samples having slightly different initial colour. The other inhomogeneity problem is that the radial surface of the specimens was used for colour measurement. It is impossible to guarantee that all individual colour measurement covers the same earlywood-latewood ratio within the measured area.

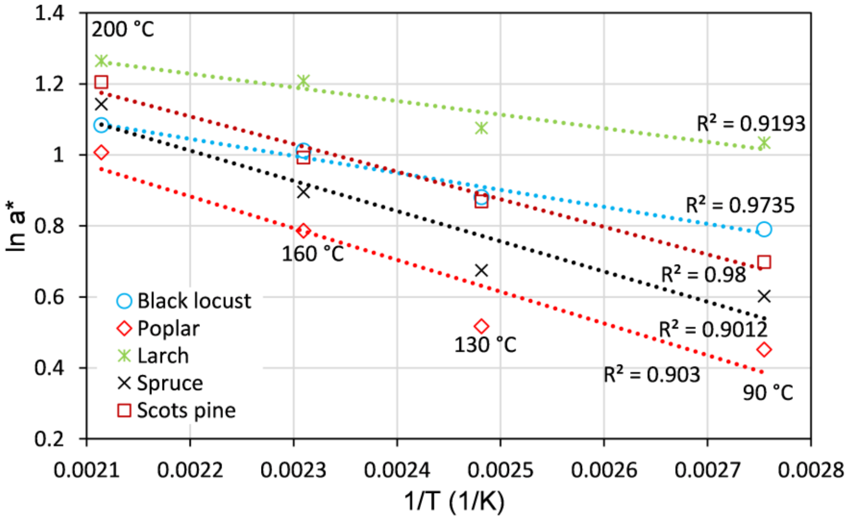

Figure 8. Arrhenius plots of redness values for black locust, poplar, larch, spruce and Scots pine species thermally treated for 6 hours at different temperatures

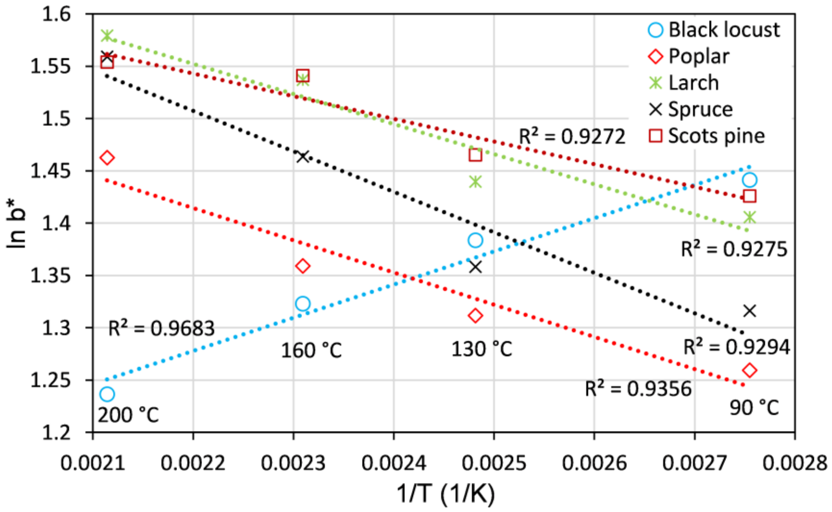

Figure 9. Arrhenius plots of yellowness values for black locust, poplar, larch, spruce and Scots pine species thermally treated for 6 hours at different temperatures

Arrhenius plots of the lightness values do not determine exactly straight lines. Fitting straight lines on the lightness dots the coefficient of determination values are much smaller (between 0.6 and 0.8) than in the case of redness and yellowness suggesting that the lightness change is determined by multiple chemical alterations generating absorption in the visible light region and the individual chemical changes are marked with different temperature dependence.

4 CONCLUSIONS

The colour modification effect of dry thermal treatment was studied in the temperature range 90-200 °C. The results showed that the 18-day treatment at 90 °C was short, while 6 hours at 200 °C was sufficient. The applied thermal treatments altered the wood colour throughout the whole cross section independently on the treatment temperature. In terms of the colour change, the extractive content of the species was dominant at low temperatures. The degradation products of hemicelluloses were the major determinant of the change in lightness at 200 °C. Redness change in percentage showed much greater alteration than the yellowness and the lightness change. Spruce presented the greatest chromaticity coordinate (a* and b*) alteration. Redness and yellowness changes followed the Arrhenius law during dry thermal treatment confirming that the temperature dependence of these colour parameters is exponential in the case of wood material.

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Basic Characteristics of Black Locust (*Robinia pseudoacacia* L.) Wood Grown Under Different Site Conditions: A Review

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Abstract – This study provides an overview of the basic characteristics of *Robinia pseudoacacia* cultivated throughout Europe. After studying the literature, we concluded that air temperature and precipitation amounts significantly influenced the annual ring width of *R. pseudoacacia*. In addition, the light, water, and nutrient supply affected tree growth by increasing growth intensity, thus reducing vessel diameters and pieces per unit area. Black locust wood grown in Belgium has a higher volumetric shrinkage (16 %) and tangential shrinkage (8.8 %) and a considerably higher modulus of elasticity (15,700 MPa) compared to wood from Poland and Hungary. The vessel diameters measured in the latewood of Robinia wood grown in Hungary (70-140 µm) exceeded those in Greece (24 µm). Knowledge of the mechanical and physical characteristics of new black locust clones wood already in cultivation via breeding is incomplete. The same applies to climate change effects. The review article recommends that future research investigate the basic characteristics of new cultivars planted in different locations.

climate change / *Robinia pseudoacacia* / environmental factors / hardwood

Kivonat – Különböző termőhelyeken nőtt akác (*Robinia pseudoacacia* L.) faanyagának alapvető jellemzői: áttekintés. A cikk célja, hogy áttekintést nyújtson az Európa-szerte termesztett fehér akác (*Robinia pseudoacacia* L.) alapvető jellemzőiről. A szakirodalmakat áttanulmányozva arra a következtetésre jutottunk, hogy az akác évgyűrűszélességét nagymértékben befolyásolta a levegő hőmérséklete és csapadék mennyisége. Ezenkívül a fény-, víz- és tápanyagellátottság befolyásolta a fa növekedését azáltal, hogy előbbiek intenzitásának növekedése csökkentette az edények átmérőjét és a területegységre jutó darabszámot. A Belgiumban termesztett akác faanyag térfogati (16 %) és tangenciális zsugorodása magasabb (8,8 %), és a rugalmassági modulus (15,700 MPa) jelentősen nagyobb a Lengyelországból és Magyarországról származó faanyagokhoz képest. A Magyarországon nőtt akác faanyagok kései pásztájában mért edényátmérők (70-140 µm) meghaladták a görögországi értékeket (24 µm). A fajtanemesítés eredményeként már termesztésben lévő új akácklónok fafaanyagának mechanikai és fizikai jellemzőire vonatkozó ismeretek hiányosak, akárcsak a klímaváltozás hatásai. Az áttekintő cikk azt javasolja, hogy a jövőbeni kutatások során vizsgálják meg a különböző termőhelyekre telepített új fajták alapvető tulajdonságait.

klímaváltozás / *Robinia pseudoacacia* / környezeti tényezők / lombosfa

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1 INTRODUCTION

The atmospheric concentration of greenhouse gases (GHG) continues to increase (Lamb et al. 2022). Consequently, these phenomena have resulted in a rise in global temperatures. For instance, in the specific case of Napkor – a region of significant black locust cultivation in Hungary – the average temperature in 2021 was 10.7 °C, representing a 0.3 °C increase compared to the mean temperature observed throughout the period spanning from 1985 to 2020. The period saw decreased precipitation (Ábri et al. 2022), drought occurrences, unpredictable rainfall patterns, flooding, biodiversity declines, and photoperiod changes, revealing some effects of GHG increase. In some areas, minerals are transferred from the soil and deposited elsewhere. These occurrences are recorded as an effect of climate change (Larchar 1995).

The growth condition consists of climatic, edaphic, and biological components. Typically, temperature, photoperiod, light intensity, moisture, soil fertility, and gravity are key factors influencing the structure of wood (Wodzicki 2001). One environmental component may be responsible for wood property variability. Conversely, interactions between two or more environmental factors and the genetic makeup of species may also occur (Kim et al. 2011).

Depending on the tree species, changes in growth conditions may affect wood quality physiologically by altering the anatomical structure of the wood, such as the number of vessels in 1mm^2, ray, parenchyma, fiber, and widths, and vessel characteristics (Usta et al. 2014, Zhang et al. 2020, Nazari et al. 2020). Additionally, the influence of tree age cannot be overlooked (Panshin – de Zeeuw 1980, Lowe – Greene 1990, Barajas 1997, Nugroho et al. 2012, Kalbarczyk et al. 2016, Kalbarczyk – Ziemiańska 2016, Keyimu et al. 2021). Understanding the impact of environmental components on wood formation is complex because it is necessary to assess the consequences of radial diameters, cell wall thickness, and other impact variables responsible for these outcomes (Arnold – Mauseth 1999).

Several studies have investigated how environmental factors influence wood structure (Farrar – Evert 1997, Rigatto et al. 2004, Ross et al. 2015, You et al. 2021). Arnold – Mauseth (1999) examined how light, water, and nutrient levels affected wood growth in *Cereus peruvianus* and demonstrated that low nitrogen and low phosphorus treatments reduced vessel width and shoot elongation, while low light reduced vessel density. Also, high moisture levels caused broader vessels and greater shoot elongation.

There is a considerable correlation between the physical and chemical soil characteristics and variation in wood quality during tree growth. While sites with suitable soil conditions are likely to produce large amounts of wood, the quality of this wood may be insufficient for structural use. Moya – Perez (2008) indicated that the physical and chemical soil properties did not affect the physical properties (specific gravity and volumetric shrinkage) of the wood in *Tectona grandis* plantations in Costa Rica. Nevertheless, Moya – Calvo (2012) mentioned that *Tectona grandis* produces a dark color with deep and fertile soil under dry conditions than in wet conditions. On the other hand, air temperature and rainfall had a notable impact on the annual ring width of *R. pseudoacacia*. Moreover, temperature and precipitation also influenced the radial cell growth, secondary wall thickening, and xylem cell generation of larch stem (*Larix sibirica*) (Antonova – Stasova 1997).

This study provides a general overview of the basic properties (physical, mechanical, anatomical, and chemical characteristics) of *Robinia pseudoacacia* wood and identifies gaps for future research.

2 THE ORIGIN AND DESCRIPTION OF BLACK LOCUST

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

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

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

R. pseudoacacia plantations occupy large areas in Bulgaria (151,000 ha), France (191,000 ha), Romania (250,000 ha), Ukraine (423,000 ha), Italy (377,000 ha), and Serbia (191,000 ha) (Nicolescu et al. 2018). It is present in 3.35% of Poland's State Forests National

Forest Holding stands (Wojda et al. 2015) and has been steadily expanding in Hungary, where it covered around 37,000 ha in 1885 and spread to about 465,000 ha in 2015, amounting to 23.8% of the total forest area (Rédei et al. 2011, Rédei et al. 2015). The species occupies around 41,919,601 ha worldwide (Ciuvăţ et al. 2013). *R. pseudoacacia* is the second hardwood species introduced for wood production in Europe after *Quercus rubra*. In Hungary, it provides 25% of the country's annual wood production (Tobisch – Kottek 2013).

R. pseudoacacia grows in the following Hungarian regions (*Figure 2*): between the Danube-Tisza interfluve (in the center of Hungary) and the northeast of Hungary (Nyírség region). It has also expanded over the south and southwest Transdanubia (the hill ridges of Vas and Zala counties and the hill ridges of Somogy County).

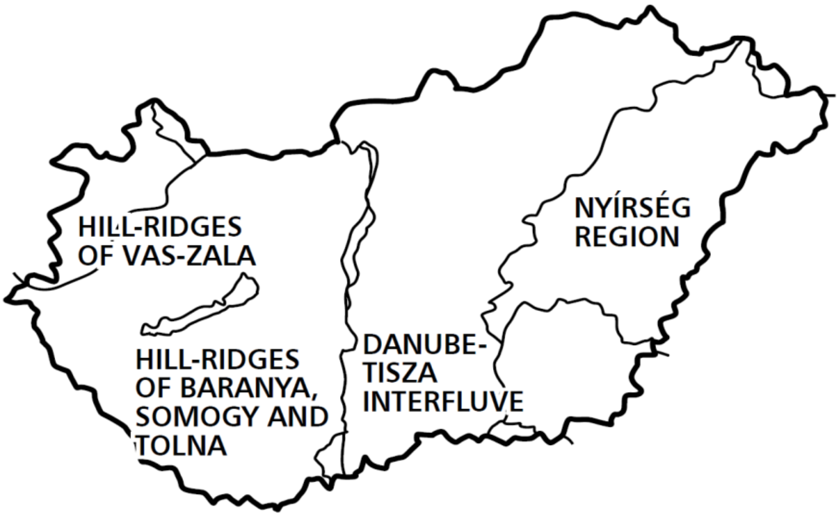

Figure 2. The main R. pseudoacacia-growing regions in Hungary. Source: (Rédei et al. 2011)

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

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

R. pseudoacacia is ring-porous (large vessels with circular arrangement) and displays heterogeneous structures (Adamopoulos – Voulgaridis 2002). The sapwood is formed of two to six annual rings and is bright yellow. Heartwood ranges in hue from yellow-brown to bluish-gray. The bark is net-like and grayish-brown (Sandor – Mahaly 2002). *R. pseudoacacia* flaws include forked or curved stems – negative for wood production – and frost sensitivity (Podrázský – Prknová 2019). Wood modification technologies (thermal and chemical modifications) have been used to improve wood properties (Kesik et al. 2014, Nemeth et al. 2016, Dzurenda 2018, Stanciu et al. 2020, Hackenberg et al. 2021, Shapchenkova et al. 2022).

Hungary has extensive experience with black locust (*R. pseudoacacia*) cultivation, having grown the species for 300 years. Several programs have been instituted in Hungary to resolve the limitations of *R. pseudoacacia* and enhance wood quality. Some of the programs generated the development of clonal materials (Rédei et al. 2012, 2013, 2019, 2020; Ábri et al. 2021, Keserű et al. 2021).

3 RESULTS AND DISCUSSION

3.1 Physical and mechanical properties

Density, moisture content, and shrinkage are the most essential physical characteristics of wood (Shmulsky – Jones 2011). Cell size and cell wall thickness are structural parameters that affect wood density. Consequently, changes in wood structure substantially affect the quality and production of pulp and paper products and the durability and usability of solid wood products. In connection with expected timber use, several mechanical properties characterize wood attributes. Strength and elasticity can be used to characterize wood properties concerning its anticipated usage (Younis et al. 2022). The mechanical properties and their correlations with other features of earlywood and latewood vary, even within the same growth ring (Desch – Dinwoodie 1996).

Stringer – Olson (1987), Sell – Kropf (1990), and other earlier researchers were interested in the basic properties of black locust wood. *R. pseudoacacia* wood is dense, brittle, extremely impermeable, and is classified as medium or semi-heavy. It has relatively low shrinkage values but shows poor dimension stability because of fiber slope (a consequence of curved logs). It is more resistant to decay, weather, and insects than most tree species indigenous to Europe (Passialis et al. 2008, Cobas 2018, Podrázský – Prknová 2019). In addition, it has a higher calorific value and ash concentration (Komán 2018). The freshly sawn wood of *R. pseudoacacia* contains only about 30% water and burns without initial drying (Wojda et al. 2015, Bijak – Lachowicz 2021). The literature on black locust reveals that age significantly impacts density, oven-dry density, basic density, porosity, shrinkage, compression strength parallel to the grain, and static bending. Similarly, significant differences in annual ring width, fiber length, and density (basic and oven-dry) of wood were revealed for 10 *R. pseudoacacia* clones aged six, eight, and 13 (Klašnja et al. 2000).

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

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

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

3.2 Anatomical features

Wood macroscopic characteristics are information-dense because they technically reveal data about the environmental conditions in which the wood grew. They also hint at its physical traits and contribute to wood identification. Understanding wood's anatomical properties can be vital to selecting the appropriate wood for end use. Anatomical features can be categorized as macro and micro.

Table 1. Literature-derived values for the average physical properties of wood R. pseudoacacia. Sources: Hungary (Molnár – Bariska 2002); Belgium (Pollet et al. 2012); Poland (Bijak – Lachowicz 2021).

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

The macro features include the growth ring and sapwood-heartwood proportion, whereas the micro features include cell characteristics and proportions, pit characteristics, micro-fibril angle, crystals, and vessel inclusions. Usually, the cells of the latewood portions are smaller in radius, have thicker walls, and have smaller lumens, making the tissue dense. (Shmulsky – Jones 2011).

Table 2. Literature-derived mean values for mechanical characteristics of wood R. pseudoacacia. CS = compression strength; JW = juvenile wood; MW = mature wood; MOE = bending modulus of elasticity; IBS = Impact bending strength. Sources: Hungary (Molnár – Bariska 2002); Hungary[b] *(Nemeth et al. 2000); Hungary*[c] *(Kamperidou et al. 2016); Poland (Bijak – Lachowicz 2021); Belgium (Pollet et al. 2012); Greece (Adamopoulos 2007).*

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

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

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

Table 3. Values of anatomical features of R. pseudoacacia wood derived from the literature. VT= vessel tissue; FL= Fiber length; VD= vessel diameter; VL= vessel length; EW= early wood; LW=late wood; GM= general mean; WEV= Wide earlywood vessel; RW= ring width. Sources: Hungary (Molnár – Bariska 2002); Greece [b] *(Adamopoulos – Voulgaridis 2002); Belgium (Pollet et al. 2012)*

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

3.3 Chemical composition

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

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

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

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

Table 4. Mean values of R. pseudoacacia chemical properties (%) derived from the literature. SW= sapwood; HW= heartwood; JW= juvenile wood; MW= mature wood. Sources: Hungary (Molnár – Bariska 2002); Hungary c (Passialis et al. 2008); Bulgaria (Passialis et al. 2008); Bulgaria ^{b} (Panayotov et al. 2015); Greece ^{c} (Passialis et al. 2008); Greece ^{d} (Adamopoulos et al. 2005); Czech Republic (Sablík et al. 2016).

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

Table 5. Literature-derived inorganic components of R. pseudoacacia wood and bark in ppm[1]. JW= juvenile wood; MW= mature wood; SW= sapwood; B= bark; HW= heartwood; Mn=Manganese; Fe= Iron; Cu= Copper; Zn= Zinc; Pb= Lead. Sources: Hungary and Bulgaria (Passialis et al. 2008); Greece (Adamopoulos et al. 2005)

previous studies	position	Ca	K	Mg	Na	P	Mn	Fe	Cu	Zn	Pb
Hungary (Clone NY)	JW	1,710	281	112	43	21	0.7	13	4.1	13	15
	MW	821	243	62	39	13	0.6	20	2.6	8.4	15
	SW	1,210	1,486	192	64	122	1.4	8.6	3.8	14	14
	B	20,967	2,592	303	466	119	7.0	59	7.9	29	35

previous studies	position	Ca	K	Mg	Na	P	Mn	Fe	Cu	Zn	Pb
Bulgaria	JW	1,658	965	168	69	15	1.8	14.4	3.1	16	24
	MW	2,462	1,046	173	68	19	1.5	10	2.7	17	12
	SW	2,371	2,634	349	70	151	3.3	15	4.4	21	23
	B	27,406	3,505	526	414	239	33	116	9.2	48	38
Greece	*Bottom*										
	HW	1,615	95	180	118	9	1	30	5	6	0.134
	SW	1,478	1,250	305	168	222	2	32	5	7	0.340
	Middle										
	HW	1,830	383	163	187	21	2	23	5	5	0.268
	SW	2,027	1,067	187	190	206	21	1	5	5	0.550
	Top										
	HW	2,013	650	158	113	35	2	21	4	4	0.088
	SW	183	1,845	617	182	198	27	2	5	6	0.257

(Table continued from previous page)

4 CONCLUSIONS

The following are some conclusions drawn from the literature review:

- Sits, soil, and tree age considerably affected the basic properties of *R. pseudoacacia*. However, tree diameter had no significant impact on latewood proportion, anisotropy, and nearly all shrinkage parameters.
- Air temperature and rainfall significantly impacted the annual ring width of *R. pseudoacacia*. Also, light, water, and nutrient levels affected wood growth by reducing vessel width and density.
- Compared to Poland and Hungary, the tangential and volumetric shrinkage of black locust wood grown in Belgium is higher. There is also a substantial increase in the modulus of elasticity.
- Black locust in plantations have a higher mechanical strength than black locust in natural and mixed forests.
- The vessel diameter in the latewood portions of Hungarian *R. pseudoacacia* is higher than its counterpart in Greece.
- The present climatic conditions and the expected changes due to global warming warrant that future research aims to investigate the properties of hybrid cultivars planted on different sites. Additionally, the currently available black locust have different natural durability levels, which need to be investigated (extract content, fungal resistance tests, outdoor tests).

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Effect of Simulated Drought and Rainfall Fluctuation on Seedling Growth of Two Savannah Trees Species in Sudan: An Experimental Exploration

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Abstract – Climate change scenarios project that several regions, especially in dryland areas of sub-Saharan Africa, will undergo increasing aridity and, subsequently, expanding land degradation. The study aims to investigate the effect of two drying treatments on establishing and growing Hashab (*Acacia senegal*) and Boabab (*Adansonia digitata*) in nursery conditions. Through a 2×2 factorial experiment, seedlings grown in a mixture of silt and sand soil (2:3) were treated by irrigation intervals of one or two liters every three days for 14 weeks to simulate rainfall fluctuation patterns. Seedling germination rate, leaf number, stem height, and diameter were measured weekly; taproot length, shoot, and root dry weights were also assessed. The results showed that neither drying treatment significantly affected *A. senegal* and *A. digitata* seedling growth parameters. However, an interaction effect was found in the height and diameter for *A. senegal* and shoot dry weight for *A. digitata*. The study concluded that *A. senegal* and *A. digitata* seem tolerant to drying treatment. Therefore, the two species are recommended for afforestation programs in areas with relatively harsher conditions. Also, exposing the seedlings of these studied species to similar, extended periods of simulated drought (e.g., 6 – 12 months) is recommended for future studies.

***Acacia senegal* / *Adansonia digitate* / climate change / dryland / Savannah /Sudan**

Kivonat – Szimulált aszály és csapadék ingadozás hatása két szavannai fafaj csemetéinek növekedésére Szudánban: egy kísérleti felfedezés. Az éghajlatváltozási forgatókönyvek szerint több régió, különösen a száraz területek a szubszaharai Afrikában, egyre szárazabbá válnak és ennek következtében a talajdegradáció is terjedni fog. A tanulmány célja a Hashab (*Acacia senegal*) és a

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Boabab (*Adansonia digitata*) két szárítási kezelésnek a csemetekerti körülmények közötti kialakulására és növekedésére gyakorolt hatásának vizsgálata. Egy 2×2 faktoriális kísérleten keresztül, amelyben magoncokat neveltünk homokos és iszapos talajkeverékben (2:3) öntözési intervallumokkal, amelyek 1 vagy 2 literes vízmennyiségeket kaptak minden 3. napon 14 hétig, hogy szimuláljuk a csapadék-ingadozásokat. A magoncok csírázási aránya, a levél- és a szár magassága, valamint átmérőjük hetente mérve lett, majd a hosszú gyökér, a hajtás és a gyökér száraz tömegeit értékeltük ki. Az eredmények azt mutatják, hogy egyik szárítási kezelés sem volt hatással az *A. senegal* és az *A. digitata* magoncok növekedési paramétereire. Azonban interakciós hatást találtunk az *A. senegal* magasságára és átmérőjére, valamint az *A. digitata* hajtás száraz tömegére. A tanulmány arra a következtetésre jutott, hogy mind az *A. senegal*, mind az *A. digitata* toleránsnak tűnik a szárítási kezeléssel szemben, ezért mindkét faj ajánlható az erdősítési programokhoz olyan területeken, ahol viszonylag szélsőségesebbek a körülmények. A jövőbeni vizsgálatok során érdemes volna a vizsgált fajok csemetéit hosszabb ideig (pl. 6-12 hónap) szimulált aszálynak kitenni.

***Acacia senegal* / *Adansonia digitate* / klímaváltozás / száraz területek / Szavanna / Szudán**

1 INTRODUCTION

Climate change poses a grave threat to the planet and its inhabitants. The Intergovernmental Panel on Climate Change (IPCC) reports that if global temperatures continue to increase at the current rate of 0.2 °C per decade, it will result in a 1.5 °C increase between 2030 and 2052 compared to the preindustrial levels (IPCC 2018). Global and regional climatic changes are expected to increase the frequency and severity of other natural hazards, such as droughts, heavy precipitation, floods, and monsoons (Grillakis 2019, Gebrechorkos et al. 2020, Carvalho et al. 2022, Aibaidula et al. 2023). According to the IPCC (2014), Sudan is projected to experience increasing temperatures, with summer averages expected to rise by 1.5 to 3.0 °C and winter averages by 1.1 to 2.1 °C by 2100. Additionally, there will be changes in precipitation patterns, characterized by a decrease in overall precipitation and increased variability, ranging from 15 % to 190 % coefficient of variation (CV). Rainfall shifts of up to 6mm and changes in the timing and length of the rainy season are anticipated. Reduced water availability will likely increase this risk and worsen land degradation (Roy et al. 2022, Chaudhuri et al. 2023). Africa has been identified as exceptionally vulnerable to the impacts of climate change; however, impacts are worse in dryland ecosystems, particularly sub-Saharan Africa (IPCC 2014, Hoffmann 2022, Ntali et al. 2023).

Drylands cover 43% of land in Africa and about 65% of the countries are dryland (Gebremeskel et al. 2021, Ren et al. 2022, Kuyah et al. 2023). Sudan is classified as a dryland country; more than half of the area is desert, 23% is a savannah ecosystem, 10% is forested, 13% is grasslands, 13% is agricultural lands, and 1% is water resources. The remainder is other (i.e., urban areas) (FAO 2013). The Savanna ecosystem in Sudan is a source of several ecosystem services, including providing livelihood and support for rural life. However, it is also a vital host of great biological diversity (Abdel Magid 2001, Siddig et al. 2019, Mohamed 2022, Mulatu et al. 2022).

Climate change is a major environmental threat to Sudan's dryland biodiversity because it reduces overall ecosystem productivity, composition, function, and vegetation diversity (Stavi et al. 2023, Abdoelmoniem et al. 2023). Savannah ecosystems are more fragile to soil erosion and lower rainfall levels. Climate extremes (e.g. drought) are highly expected in Sudan because rainfall patterns in savannas link directly to climate change, rising temperatures, and the El Nino phenomenon. Subsequently, tree species will likely suffer from water scarcity, reflected in species distribution and patterns in savannas and woody land (Huang et al. 2022, Delgado et al. 2022, Dahan et al. 2023). Desertification is likely to complicate the impacts of climate change on savannah ecosystems as the Sahara Desert expands rapidly southwards (Ardi 2013).

Hashab (*Acacia senegal*) is a priority dryland species, a crucial component of traditional dryland agroforestry resilience systems, and a source of livelihood in Sudan (Mohamed et al. 2015, Deng et al. 2017, Gadallah et al. 2022, Hasoba et al. 2020, Hemida 2023). *A. senegal* is a multi-purpose tree that produces gum arabic, a high-value export commodity in Sudan and other African countries (Peroches et al. 2022). The tree also provides animal fodder, multiple timber products, intercropping, firewood, food, and medicines (Fadl – El Sheikh 2010, Peroches et al. 2022). Furthermore, it is one of the most significant sub-Saharan African trees inhabiting savannah systems to be threatened by ongoing anthropogenic and climate-mediated degradation, leading to substantial losses of natural habitats (Marchant 2022, Abdoelmoniem et al. 2023). The tree is found to be more responsive to its limited growth factors, especially by availing water in the seedling stage (Abdoelmoniem et al. 2023).

The Baobab tree (*Adansonia digitata*) is widely distributed in Africa, forming a belt in central Sudan (Elamin 1990, Adesina – Zhu 2022, Elsayed et al. 2023). *A. digitata* is a valuable savanna tree for food, fodder, and medicine it provides animals and humans (Leakey et al. 2022, Bosch et al. 2004, Saeed et al. 2023). The European Union approved the species as a novel food in 2008, granting African farmers access to a billion-dollar industry (Hermann 2009, Meinhold et al. 2022, Leakey et al. 2022). Nicknamed the *Tree of Life*, the endangered baobabs play a significant role in their ecosystem by keeping soil conditions humid, promoting nutrient recycling, and preventing soil erosion. Additionally, they are a vital source of food, water, and shelter for various animals, birds, reptiles, and insects (Nayak et al. 2022).

Drought stress at germination and seedling emergence stages may have a series of disastrous consequences on the dynamics of species. For instance, a lack of natural regeneration and the decline of *A. senegal and A. digitata* populations have been commonly observed in Sudan (Fischer 2020, Mohammed 2021). However, the link between drought resistance and plant distribution and diversity of the two species needs to be better understood. The present study focuses on the effects of simulated drought and rainfall fluctuations on seedling growth, providing insights into how changing environmental conditions can affect tree species. This study is relevant because it explores the tree seedling responses to simulated drought and rainfall fluctuations within a savanna setting. Understanding the influence of these factors on seedling growth can provide valuable insights into the resilience and adaptability of tree species, which is relevant not only in Sudan but also in other ecosystems, including those in Central Europe. This paper aims to experimentally investigate drought impacts on the establishment and development of these two species.

2 MATERIALS AND METHODS

2.1 Seed source

A. senegal and *A. digitate* seeds were collected from trees growing naturally in the Elain Natural Forest Reserve (12º 52′ -13º 04′ N and 30º 10′-30º 24′ E), 26 km south of Elobeid, the capital of North Kordofan State, Sudan. The forest falls under savannah low rainfall and receives annual rainfall between 300-600 mm.

2.2 Study site and settings

The experiment was conducted in the nursery facility in the Faculty of Forestry at the University of Khartoum, Shambat Area (latitude 15º40 N, longitude 32º 32 E and height 380 m above sea level) (*Figure 1*) from December 2017 to March 2018. Annual precipitation of 14.28 mm, annual temperatures (min. 24.76ºC, max. 37.25 ºC), relative humidity of 22.53 %, and dense vegetation adjacent to the eastern bank of the river Nile characterize the region.

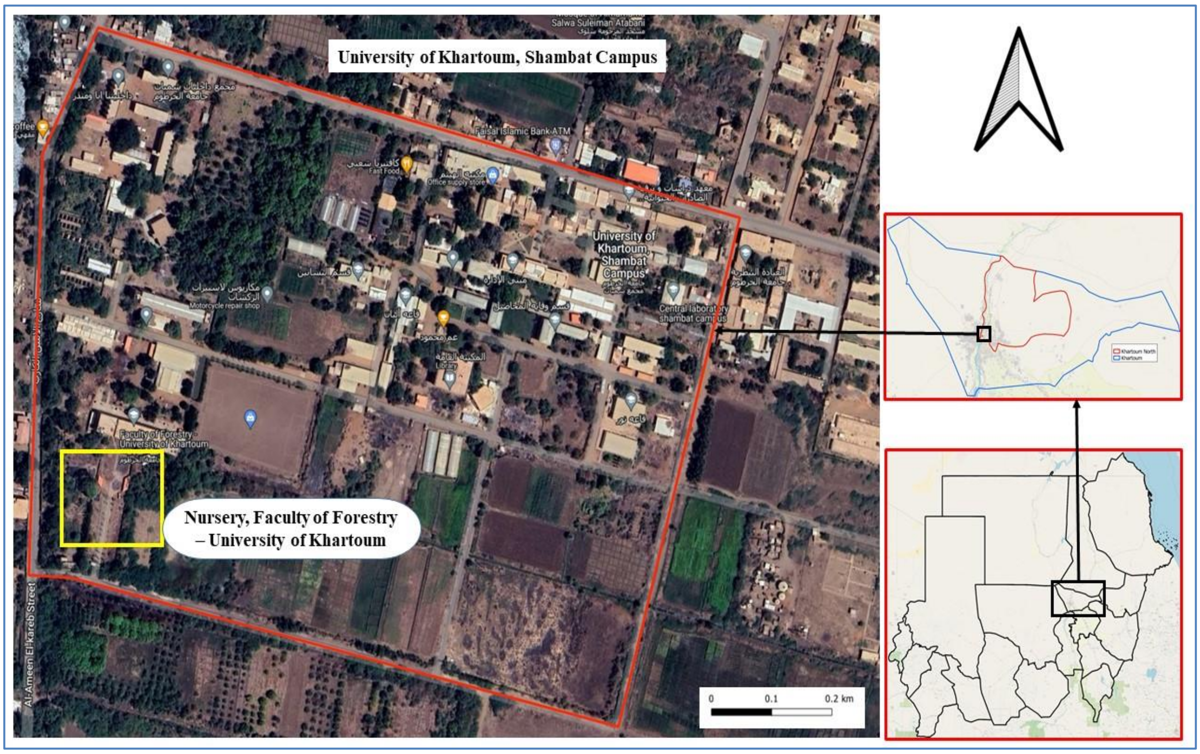

Figure 1. Map of the study area.

2.3 Experimental design and treatments

The study simulated drought and rainfall fluctuation effects on the seedling growth of two savannah tree species in an area with annual rainfall between 300-600 mm. The experiment design was through a 2×2 factorial study. The treatments were drought occurrence (i.e., drought occurs or does not occur) and drought pattern (i.e., occurs regularly or randomly).

The study collected 250 grams of *A. senegal* and *A. digitata* seeds from the Kordofan region and sowed three seeds of each species in 24 pots (six seeds per pot; 72 seeds). Irrigation in the first three weeks was two liters in three-day intervals, assigned to normal condition (no drought) units. An irrigation interval of one liter every three days was assigned to drying units (drought conditions). From week four to week 14, irrigation intervals used to simulate rainfall fluctuations were assigned randomly to the pots by adopting two weeks of irrigation breaks. Consultations with hydrology and climatology experts determined the water amounts used for irrigation in the experiment. The study also considered natural rainfall patterns in the low-rainfall Savannah, which typically ranges between 300 and 600 mm.

2.4 Measured variables

The study monitored seedling germination, growth, and survival weekly. Germination was observed for the presence or absence of newly germinated seeds, seedling height, diameter, and number of leaves. Then plants were harvested and separated into shoot and root, where the tap root lengths were measured. Shoot and root dry weight was determined by oven drying for 24 hr at 105 ºC. Soil characteristics were also assessed by conducting before and after treatments following the same sample quantity. In particular, Electric Conductivity (EC) pH, Sodium Adsorption Ratio (SAR), and Field Capacity (FC) were measured (Pachepsky – Rawls 2005).

2.5 Statistical methods

The Analysis of Variance (ANOVA) procedures and Duncan's Multiple Range Test were applied to separate means of the same factor that were performed using the R open-source software program (R core team 2021), and simple summary descriptive statistical methods were used.

3 RESULTS

3.1 Effect of simulated drying and rainfall fluctuation pattern on the development and growth of *A. senegal* seedlings

Drying and rainfall fluctuation patterns did not significantly affect *A. senegal* seedling height, diameter, leaf number, taproot length, and shoot and root dry weights ($P < 0.05$, *Table 1*). However, the interaction effect of drying and fluctuation was significant on seedling height and diameter ($F_{1, 20} = 5.522$, $P < 0.05$) and ($F_{1, 20} = 4.902$, $P < 0.05$), respectively.

Table 1. Results of ANOVA test for effects of simulated drying and rainfall fluctuation pattern on A. senegal seedling growth

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Shoot Height					
Drying	1	20.17	20.17	2.817	0.1088
Fluctuation	1	11.48	11.48	1.604	0.2199
Drying: Fluctuation	1	39.53	39.53	5.522	0.0292 *
Residuals	20	143.16	7.16		
Number of Leaves					
Drying	1	40	39.8	0.207	0.6539
Fluctuation	1	3	3.2	0.016	0.8993
Drying: Fluctuation	1	727	727.1	3.786	0.0659
Residuals	20	3841	192.0		
Root Length					
Drying	1	65	65.0	0.333	0.5704
Fluctuation	1	53	52.5	0.269	0.6098
Drying: Fluctuation	1	721	720.5	3.689	0.0692
Residuals	20	3907	195.3		
Biomass					
Drying	1	63	63.1	0.309	0.5844
Fluctuation	1	49	49.0	0.240	0.6293
Drying: Fluctuation	1	734	733.7	3.596	0.0724
Residuals	20	4080	204.0		
Plant Diameter					
Drying	1	0.02667	0.02667	3.137	0.0918
Fluctuation	1	0.01500	0.01500	1.765	0.1990
Drying: Fluctuation	1	0.04167	0.04167	4.902	0.0386 *
Residuals	20	0.17000	0.00850		
Root Dry Weight					
Drying	1	0.015	0.0150	0.091	0.766
Fluctuation	1	0.060	0.0600	0.363	0.553
Drying: Fluctuation	1	0.060	0.0600	0.363	0.553
Residuals	20	3.303	0.1652		
Shoot Dry Weight					
Drying	1	0.0417	0.04167	0.725	0.4047
Fluctuation	1	0.0017	0.00167	0.029	0.8665
Drying: Fluctuation	1	0.2400	0.24000	4.174	0.0545
Residuals	20	1.1500	0.05750		

3.2 Effect of simulated drying and rainfall fluctuation pattern on the development and growth of *A. digitata* seedlings

Drying and rainfall fluctuation patterns did not significantly affect the *A. digitata* seedling height, diameter, leaf number, taproot length, and shoot and root dry weights. However, a significant interaction effect was found on shoot dry weight ($F_{1, 20} = 4.17$, $P = 0.05$; *Table 2*), root length (P= 0.06), and biomass (P=0.07).

Table 2. Results of ANOVA test for effects of simulated drying and rainfall fluctuation pattern on A. digitata seedling growth.

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Shoot Height					
Drying	1	2.34	2.344	0.293	0.594
Fluctuation	1	0.01	0.010	0.001	0.972
Drying: Fluctuation	1	0.84	0.844	0.105	0.749
Residuals	20	160.13	8.007		
Number of Leaves					
Drying	1	5.42	5.423	1.036	0.321
Fluctuation	1	0.46	0.459	0.088	0.770
Drying: Fluctuation	1	0.46	0.459	0.088	0.770
Residuals	20	99.43	5.233		
Root Length					
Drying	1	65	65.0	0.333	0.5704
Fluctuation	1	53	52.5	0.269	0.6098
Drying: Fluctuation	1	721	720.5	3.689	0.0692
Residuals	20	3907	195.3		
Biomass					
Drying	1	77	63.2	0.312	0.5855
Fluctuation	1	50	49.22	0.250	0.6288
Drying: Fluctuation	1	735	733.7	3.595	0.0722
Residuals	20	4090	204.0		
Plant Diameter					
Drying	1	0.0104	0.010417	0.652	0.429
Fluctuation	1	0.0012	0.001157	0.072	0.791
Drying: Fluctuation	1	0.0012	0.001157	0.072	0.791
Residuals	20	0.3194	0.015972		
Root Dry Weight					
Drying	1	0.0150	0.01500	0.0908	0.7663
Fluctuation	1	0.0600	0.0600	0.363	0.553
Drying: Fluctuation	1	0.0600	0.0600	0.363	0.553
Residuals	20	3.3033	0.16517		
Shoot Dry Weight					
Drying	1	0.0412	0.04157	0.721	0.4027
Fluctuation	1	0.0015	0.00144	0.025	0.8625
Drying: Fluctuation	1	0.2200	0.2477	4.17	0.0542
Residuals	20	1.1700	0.05780		

3.3 Effect of simulated drying and rainfall fluctuation pattern on soil conditions of the two studied species

Drying significantly affected SAR ($F_{1, 20} = 13.91$, $P < 0.01$) but not on other variables. Further, rain fluctuation patterns showed no significant effects on any measured variables (FC, EC, pH, and SAR). On the other hand, the interaction effect was marginal on soil pH ($F_{1, 20} = 3.689$, $P = 0.06$, *Table 3*).

Table 3. Results of ANOVA test for the effect of simulated drying and rainfall fluctuation pattern on soil

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Field Capacity (FC)					
Drying	1	2.60	2.600	0.372	0.549
Fluctuation	1	0.77	0.770	0.110	0.743
Drying: Fluctuation	1	0.07	0.070	0.010	0.921
Residuals	20	139.91	6.995		
Electrical Conductivity (EC) – Salinity					
Drying	1	0.0067	0.00667	0.087	0.772
Fluctuation	1	0.1067	0.10667	1.385	0.253
Drying: Fluctuation	1	0.1067	0.10667	1.385	0.253
Residuals	20	1.5400	0.07700		
pH					
Drying	1	65	65.0	0.333	0.5704
Fluctuation	1	53	52.5	0.269	0.6098
Drying: Fluctuation	1	721	720.5	3.689	0.0692
Residuals	20	3907	195.3		
Sodium Adsorption Ratio (SAR)					
Drying	1	0.20167	0.20167	13.91	0.00132 **
Fluctuation	1	0.00667	0.00667	0.46	0.50550
Drying: Fluctuation	1	0.00667	0.00667	0.46	0.50550
Residuals	20	0.29000	0.01450		

3.4 Trend of growth and development factors of two studied species:

The trend of seedling response to drying and rain fluctuation treatments was moderate and varied between the species. As the following figures show (Figures 2, 3, 4, and 5), the number of leaves on Hashab seedlings increased in the first seven weeks for all treatments before decreasing in the last three weeks. The interaction of drying and fluctuations significantly increased the number of leaves compared to the independent (main) treatment (*Figure 2*). The results are as expected if the drying fluctuations are discounted; however, the drying fluctuations influenced the results unexpectedly.

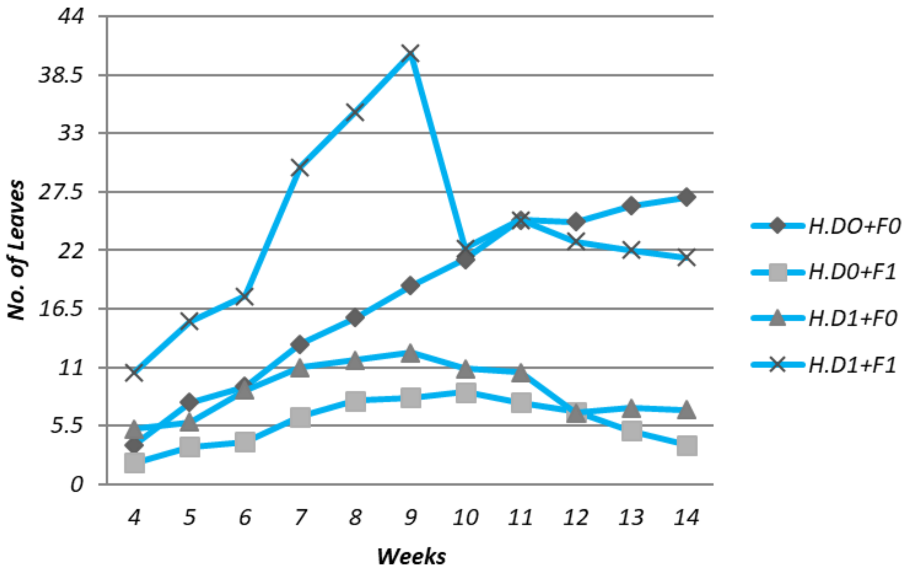

Figure 2. The trend of weekly changes in the number of leaves for Acacia senegal (H) seedlings. D = Drying treatment & F = Drying fluctuation pattern treatment; 1 = treatment present; 0 = treatment absent.

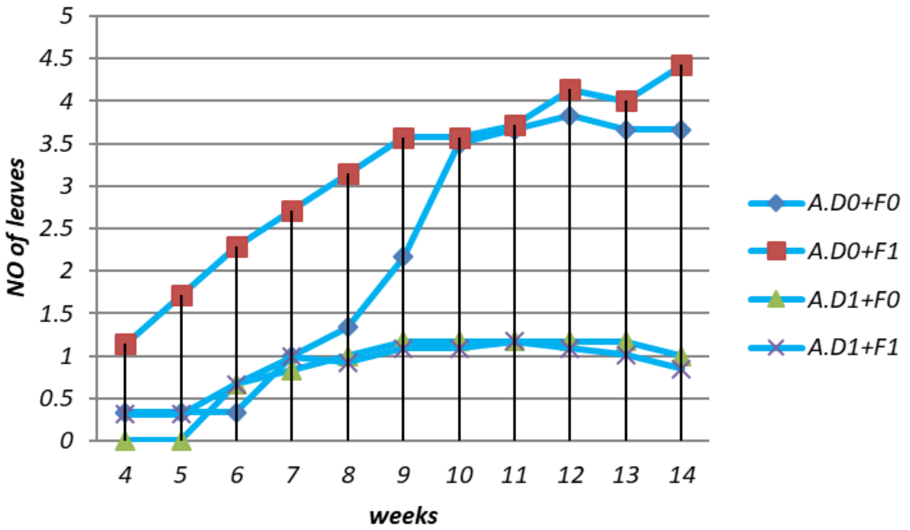

Figure 3. The trend of weekly changes in the number of leaves for Adansonia digitata (A) seedlings. D = Drying treatment & F = Drying fluctuation pattern treatment; 1 = treatment present; 0 = treatment absent.

Adansonia seedlings responded negatively to the drying and fluctuation treatments, as the number of leaves in the treated pots showed a declining trend compared to the control (*Figure 3).* Seedling height for Hashab trees showed an increasing trend because the interaction effects of the two treatments seemed higher than the control (*Figure 4*). On the other hand, the height of Adansonia seedlings in the interactive treatments showed a steady, stable trend compared to the control treatment (*Figure 5*).

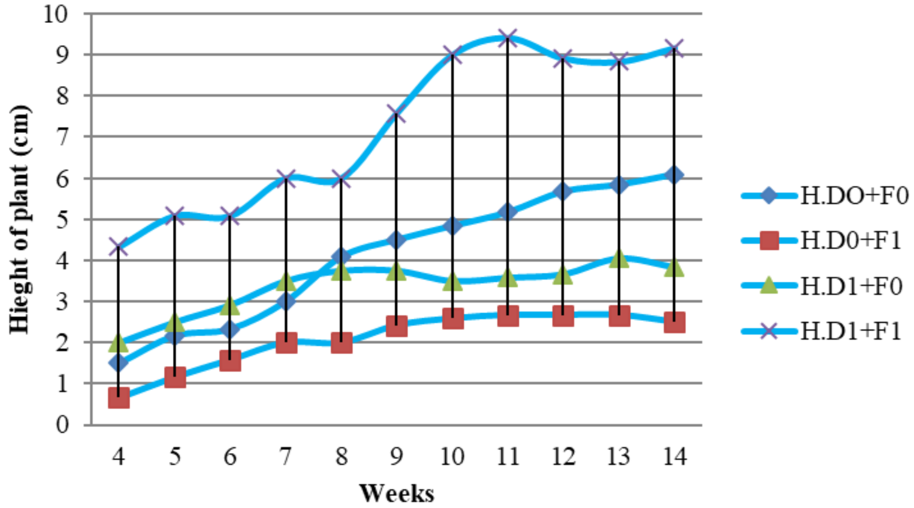

Figure 4. The trend of weekly changes in seedling height for Acacia senegal (H). D = Drying treatment & F = Drying fluctuation pattern treatment; 1 = treatment present; 0 = treatment absent.

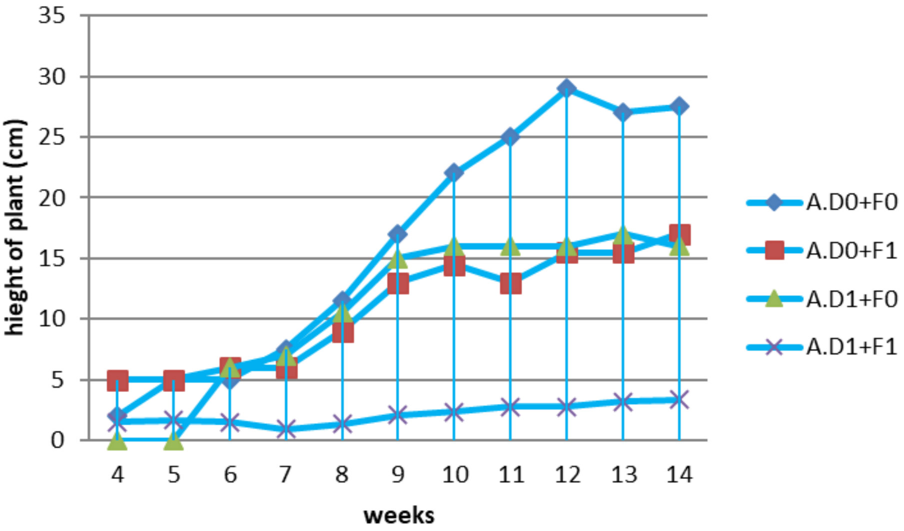

Figure 5. The trend of weekly changes in seedling height for Adansonia digitata (A). D = Drying treatment & F = Drying fluctuation pattern treatment; 1 = treatment present; 0 = treatment absent.

4 DISCUSSION

The present study tested the effect of the simulated drought and drying pattern on *Acacia senegal* and *Adansonia digitata* seedling establishment in nursery conditions. It provides valuable information about these species' potential for adapting to future climate change scenarios by exposing them to controlled environmental stressors. Sustainable reforestation and afforestation programs can benefit from the findings because they can aid in selecting tree species that do well in varying climates. The study's rigorous experimental design ensures accurate results and adds to our knowledge of how to preserve the savannah ecosystems of Sudan. The findings also help with climate-resilient land use planning and provide insight into broader ecological implications.

Our results showed some significant effects and varied impacts of drying and watering fluctuation patterns within and between the two species in some of the parameters investigated. Seedling growth of the two species, as measured by the number of leaves and plant shoot height, showed some negative responses to the treatments. Results were consistent with our early assumptions and literature about plant responses to environmental changes in dryland (Schreiner-McGraw et al. 2020, Sun et al. 2021, Wang et al. 2022). Studies have also reported that trees native to arid environments often have a high root/shoot ratio; the higher the exposure to drought, the more the ratio between root and shoot mass shifted further in favor of root growth (Larcher 1995, Lozano et al. 2022, Wu et al. 2023) and was found in many dry zone plants, including *Acacia tortilis, Acacia senegal,* and *Acacia mellifera* (Elmagboul 2002, Musa 2005, Retta et al. 2022, Zwarts et al. 2023).

Many studies proved that a lack of rainfall is the main reason for low Baobab seedling survival in several countries (Sanchez 2011, Hellion–Gusted 2004, Venter – Kwiatkowski 2013, Fischer et al. 2020). However, Schweiger et al. (2020) have projected that efficient Baobab recruitment may occur every 100–150 years. Thus, in the absence of Baobab regenerations, episodic recruitment could maintain Baobab populations (Sanchez 2011, Venter 2012, Venter – Kwiatkowski 2013, Msalilwa et al. 2020, Orina et al. 2021).

Acacia senegal seedlings were more tolerant than *Adansonia digitata* seedlings in response to drying and drying fluctuation patterns suggesting that plants can adapt to drought conditions by shedding older leaves. Drought resistance differences in species may be a crucial factor influencing species distributions in the dry tropics. However, the link between species drought resistance and plant distribution and diversity needs to be better understood, mainly because comparative quantitative assessments of the effects of drought on plant growth and survival are largely missing. We use drought resistance as "the capacity of a plant to withstand periods of dryness" (Larcher 2000), i.e., the ability to survive drought while minimizing reductions in growth and, ultimately, fitness.

On the other hand, increasing drying conditions affected the total plant dry weight for both studied species. Although *Acacia senegal* seedlings showed higher total plant weight, the two species no significant weight differences during the experiment. Indeed, this indicates the tolerance of *Acacia senegal* to survive arid conditions with reasonable growth performance and biomass buildup. Furthermore, the observed higher root/shoot ratio in *Acacia senegal* indicates that this species is more prone to survive dry conditions.

Both species can withstand drying and watering fluctuations, indicating their resistance against anticipated drought conditions. However, *Acacia senegal* seedlings seem more tolerant to drought and rain breaks than Adansonia digitata seedlings.

5 CONCLUSIONS

This study concludes with significant insights regarding the effects of simulated drought and drying patterns on the growth and development of *Acacia senegal* and *Adansonia digitata* seedlings. The findings suggest that the two species have different tolerance levels to drying treatments, with *Acacia senegal* seedlings demonstrating greater tolerance than *Adansonia digitate* seedlings. The drought resistance differences between the two species may significantly influence their distributions in the dry tropics. The study also highlights the importance of water harvesting techniques and protection from browsing animals and humans during afforestation projects involving these two species. Additionally, the results suggest that further research is needed to assess the impacts of longer drying intervals on the growth and development of both seedlings and to investigate their sensitivity to other climate change factors, such as heat waves and temperature rises. In light of the findings, the study recommends prioritizing *Acacia senegal* for afforestation programs in areas with more arid conditions and that special programs be developed for Baobab afforestation focusing on drying tolerance for seedlings and protection from browsing. Nevertheless, the results of this study warrant caution as they are of only are from only one experiment with relatively low replications. Overall, this study contributes to our understanding of the effects of drying on seedling survival and dynamics and provides valuable insights into the management of afforestation projects in dry tropics.

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Ethnobotanical Study on Some Tree Species Used as Bioenergy in South Darfur State, Sudan

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Abstract – This study provides ethnobotanical information on preferred local energy tree species based on biomass characteristics. The survey used a stratified sampling technique. The questionnaire covered different issues related to the consumers and biomass characteristics for energy utilization. The study computed use value, fidelity level, and factor informant consensus for the most frequently used energy tree species. According to the highest use values, respondents in the study area identified *Acacia mellifera* and *Capparis decidua* as the most vital energy tree species. Sustained combustion is the most desired property for brickmaking, while bakeries and homes prefer haste ignition. Further research and laboratory testing of tree characteristics of selected species in energy plantations and agroforestry programmes in Sudan could help confirm the study results.

ethnobotany / biomass / energy utilization / sustained combustion

Kivonat – Etnobotanikai tanulmány néhány bioenergiaként használt fafajról Dél-Darfúr államban, Szudánban. Jelen tanulmány célja az volt, hogy a biomassza jellemzői alapján jelentős etnobotanikai információkat nyújtson az energetikai célokra preferált helyi fafajokról. A felmérés rétegzett mintavételi technikával készült. A kérdőív a fogyasztókkal és a biomassza energiahasznosítási jellemzőivel kapcsolatos különböző kérdésekre terjedt ki. A leggyakrabban használt fafajoknál az energia, használati érték, hűségszint és faktorinformátor konszenzust számoltuk. A legmagasabb használati értékek szerint a válaszadók megemlítették, hogy a vizsgált területen az *Acacia mellifera* és a *Capparis decidua* a legfontosabb energiafafaj. A tartós égés a legkívánatosabb tulajdonság a téglagyártásnál, míg a pékségekben és a háztartásban a gyorsgyújtást részesítik előnyben. Ezért a vizsgálat eredményeit a kiválasztott fajok jellemzőinek további kutatásával és laboratóriumi ellenőrzésével kell megerősíteni. Annak érdekében, hogy beépítsék őket az energiaültetvényekbe és az agroerdészeti programokba, mint jövőbeli energiafajokat Szudánban.

etnobotanikai / biomassza / energiahasznosítás / fenntartó égés

1 INTRODUCTION

Biomass can help solve global energy problems because it is renewable and environmentally sound (Solarin et al. 2018). Many countries, including those in Africa, are increasing their biomass production for energy use. About 87 % of primary energy consumption in Sudan originates from biomass (Galal 1997). Biomass is the chief energy source in rural areas and

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towns, particularly those with less *LPG* (liquefied petroleum gas) distribution in Sudan. Biomass energy serves numerous domestic purposes, including cooking, heating, bakeries, and brick production. Increasing energy needs in Sudan due to the growing population and IDPs (internally displaced people) has caused significant overexploitation and depletion of forest resources and has affected the species used for energy, as stated by United Nations Environmental Program (UNEP 2008). The change from conventional species with traditionally favourable energy properties to new species with low energy quality may put the new species under pressure and deplete species with desirable energy properties. Thus, rehabilitating the degraded species is required shortly after; however, it is particularly crucial before selecting species selection as a biomass feedstock source because of the effect on the different fuel properties (Neves et al. 2011, Jacob-lopes et al. 2019). Assessing biomass quality is vital to its utilization feasibility because combustion is a dominant feature of converting biomass fuel to energy in Sudan. Some significant biomass combustion properties deserve attention, including biomass moisture content, density, and ash content. When high moisture content affects transport, storage and energy content, the proper moisture content ratio for combustion must be less than 20%. Concerning biomass density, it has a positive relationship with heating value. For this reason, experts state it should be as high as possible (Meincken et al. 2014), while ash content should be as low as possible due to its negative heat value correlation (Ahmed 2021).

Along with state plans for energy plantations, appropriate species with ideal efficient energy and sustainable biomass supply properties must be selected. Alternative sustainable approaches are needed to keep pace with the growing demand for biomass feedstock. This study pursued ethnobotany methods to gain knowledge from local people concerning the desired properties of local energy production species and document this scientifically. Consequently, the study bases its findings and suggestions on consumer preferences, which may be valuable for decision-makers in predicting suitable and preferable species.

2 MATERIALS AND METHODS

2.1 Study area

The study area was selected based on UNEP (2008) reports which revealed information on biomass fuel consumption in Sudan. We selected South Darfur State (*Figure 1*), which is reported by UNEP (2008) as having the highest wood fuel consumption and population in Sudan. The study area extends between latitudes 8°30′ to 13°′N and longitudes 23°15′to 28°E (Abaker et al. 2017) in open thorn savannas with sparse arboreal cover. Acacia species is the dominant plants formations in the study area. The selected area lies in a subtropical steppe climate where the average temperature during the hottest month of April is 41 °C (105 °F), while the average low temperature during the coldest month of January is 15 °C (59 °F). The region receives low rainfall amounts, with most precipitation falling from July to September. The annual average precipitation is approximately 311 mm (12 inches) and falls in erratic and unpredictable patterns. Dust storms occur during the dry season, especially in March and April (Morton 2005).

Figure 1. Study area location in Sudan

2.2. Data collection

Primary and secondary data were gathered using combined qualitative and quantitative data collection methods. Field survey was conducted in September 2021 to collect primary data from Kalma IDP Camp, Nyala District, South Darfur State, Sudan. Key informants, including experts from the Forest National Corporation (FNC) and individuals who have first-hand information, such as firewood dealers, were interviewed to collect information about the appropriate bioenergy species. A stratified random sampling technique was employed to collect information from three respondent strata; households, brick kiln owners and bakers with sample ratios of 3:1:1, respectively. The questionnaires were designed to cover different issues related to major energy species, preferences energy characteristics and consumption categories. Ninety-two respondents of different ages and sex (males and females) were interviewed. Furthermore, group discussions were held with the local leaders to complement and verify the data collected through the consumer survey.

2.3. Data analysis

The questionnaire data were transformed into codes. Statistical Package for Social Sciences (version 26) software was used in the analysis. Frequency distribution and percentage were calculated as an analysis tool for interpreting the qualitative information collected from the respondents. The use value was calculated to discover the proportional importance of energy tree species to each consumer category in the study area. It was calculated by the following equation 1:

$$\mathrm{UV} = \frac{\sum \mathrm{Ui}}{\mathrm{n}} \tag{1}$$

Where *UV* stands for the total use value of the energy trees species, while *U* refers to the number of use reports cited by each respondent for a given species, and n stands for the total number of respondents interviewed for a given species Fidelity level (*FL*) was also computed to determine the *FL* values of the most frequently used tree species for energy. Formula 2 was employed in the calculation:

$$FL = \frac{\mathrm{NP}}{\mathrm{n}} \tag{2}$$

Where *NP* stands for the number of use reports cited for a given species for a particular use, and N refers to the total number of use reports cited for any given energy species. Factor informant consensus (*FIC*) was also calculated to identify the tree species widely used for energy. The FIC can be calculated using equation 3:

$$FIC = \frac{\text{nur}-\text{nt}}{\text{nur}-1} \tag{3}$$

Where *FIC* = informants consensus factor, nur = number of use citations in each category, and *nt* = number of species used (Khan et al. 2014).

3 RESULTS AND DISCUSSION

This study documented 18 indigenous tree species in 14 genera and 11 families used for energy purposes (*Table 1*). The plant family Mimosoideae contributed the highest number of energy tree species (6), followed by Combretaceae (3) and Fabaceae (2) (*Table 1*). Among the total documented energy tree species, respondents stated that *Acacia seyal* (60%) is the most preferred species for domestic use, followed by *Calotropis procera* 22 % (*Figure 2*). *Calotropis procera* is of lower quality than other species such as *Acacia seyal*, *Acacia mellifera* and *Acacia nilotica*; however, they are utilized because the degeneration of desirable species forces households to use lower-quality wood. This result agrees with the UNEP report (2008), which noted the overexploitation of local tree species due to energy needs, causing significant depletion in forest resources and changes concerning the species typically used for energy. Results showed that bakeries prefer *Acacia mellifera* 72%, *Acacia nilotica* 16% and *Albizia amara* 12 % (*Figure 2*), whereas brickmakers preferred *Acacia nilotica* by a 70% ratio, followed by *Acacia mellifera* 17 % and *Vachellia tortilis*13 % (*Figure 2*). Brickmaking and baking require a particular biomass property; for example, about 56% of respondents named sustainable combustion the most desired brickmaking property (*Figure 3*). Sustainable combustion is the time between flame extinction and residence time. Prior et al. (2018) state that brickmakers prefer long fuel combustion residence time. USAID (2008) reported that brickmakers prefer slow-burning fuel because bricks take much longer to bake than bread. Brickmakers will occasionally also use green wood instead of dead wood for this purpose. Bakeries preferred haste ignition and low smoke, 52% and 27%, respectively (*Figure 3*). Individual interview statements cite ignitability as a vital property for bakeries because baking bread does not take long. However, bakeries consider high smoke levels from pollutant emissions such as NO_2 and SO_2 undesirable because they pose potential health risks to bakery workers (Ahmed 2021). People in the study area assign priority to some traditional energy tree species, including *Acacia mellifera*, *Acacia nilotica*, *Acacia seyal*, *Vachellia tortilis*, *Albizia amara*, *Calotropis procera*, *Balanites aegyptiaca*, *Hayphaene thebaica* and *Dalbergia melanoxylon* (*Table 1*). The use values (*UV*) results revealed that *Acacia mellifera* 0.51 and *Acacia nilotica* 0.42 are the most important energy tree species compared to other local tree species (*Table 2*).

Table 1. The common energy trees species in the study area

No	Family	Species	Local name
1	Arecaceae	*Hyphaene thebaica*	Dom
2	Asclepiadaceae	*Calotropis procera*	Oshar
3	Capparaceae	*Capparis decidua*	Tundob
4	Combretaceae	*Anogeissus leiocarpa*	Sahab
5	Combretaceae	*Combretum ghasalense*	Habil
6	Combretaceae	*Guiera senegalensis*	Khebash

No	Family	Species	Local name
7	Fabaceae	*Acacia mellifera*	Kiter
8	Fabaceae	*Acacia nilotica*	Sonut
9	Fabaceae	*Acacia senegal*	Hashab
10	Fabaceae	*Acacia seyal*	Talah
11	Fabaceae	*Albizia amara*	Arad
12	Fabaceae	*Faidherbia albida*	Haraz
13	Fabacea	*Dalbergia melanoxylon*	Abanus
14	Fabaceae	*Prosopis chilensis*	Miskeet
15	Fabaceae	*Vachellia tortilis*	Seyal
16	Rhaminaceae	*Ziziphus muritania*	Sider
17	Salvadoraceae	*Salvadora persica*	Arak
18	Zygophylaceae	*Balanites aegyptiaca*	Higlig

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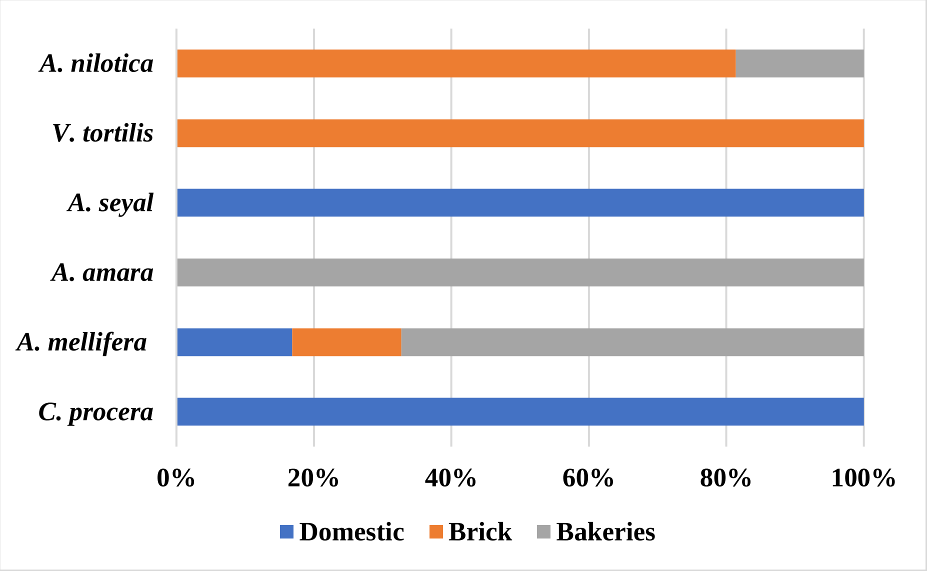

Figure 2. Preferred energy tree species according to utilization categories

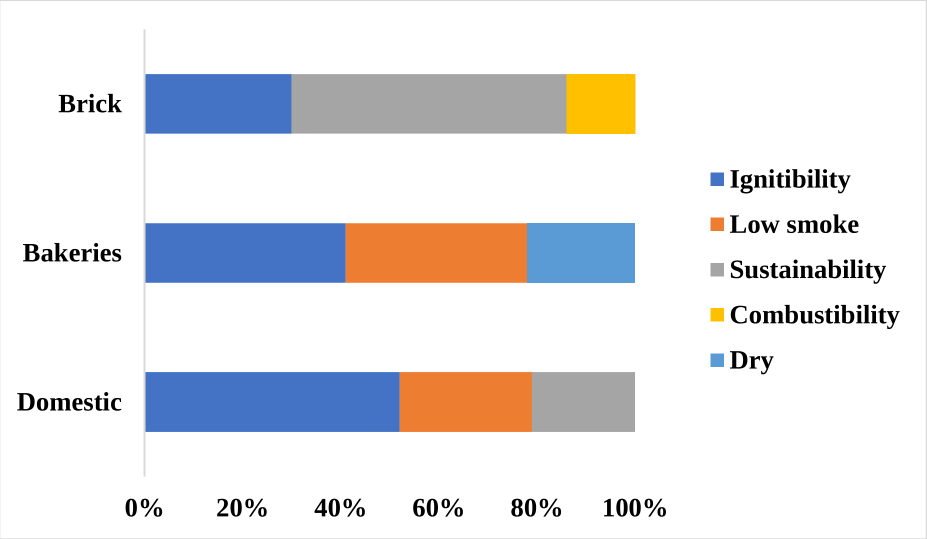

Figure3. Preferred energy characteristics by utilization categories

Table 2. The use values (UV) of local energy tree species

No	Species name	Number of use reports $\sum \mathbf{Ui}$	Use value UV
1	*Calotropis procera*	27	0.29
2	*Acacia mellifera*	47	0.51
3	*Albizia amara*	23	0.25
4	*Acacia seyal*	1	0.01
5	*Dalbergia melanoxylon*	37	0.40
6	*Vachellia tortilis*	7	0.07
7	*Acacia nilotica*	30	0.33
8	*Capparis decidua*	39	0.42
9	*Anogeissus leiocarpus*	2	0.02
10	*Balanites aegyptiaca*	2	0.02
11	*Ziziphus muritania*	12	0.13
12	*Guiera senegalensis*	3	0.03
13	*Faidherbia albida*	1	0.01
14	*Acacia senegal*	6	0.07
15	*Salvadora persica*	1	0.01
16	*Hayphaene thebaica*	5	0.05
17	*Prosopis chilensis*	1	0.01

Informant consensus factor (*FIC*) results show that sustainability scored as the highest *FIC* value (0.89), followed by combustibility (0.88) and ignitibility (0.85), which were also the top recorded biomass properties preferred by informants (*Table 3*). A high *FIC* value indicates that these properties are more prevalent in the study area.

Table 3. FIC values of traditional energy trees species properties in the study area

Properties categories	Number of species (*Nt*)	Number of properties report (*Nur*)	Consensus factor
Sustainability	11	90	0.89
Combustibility	11	84	0.88
Ignitibility	9	54	0.85
Dry	3	9	0.75
Low smoke	5	12	0.64

Energy species local people widely use have higher FL values than those of less popular species. FL values in this study varied from 34% to 83%. *Acacia seyal* has a high value of 83 %, characterized by high combustibility, followed by *Acacia nilotica* at 69 % and *Albizia amara* at 34 %, characterized by sustainable combustion. *Vachellia tortilis*, 56 %, and *Acacia mellifera*, 36 %, are characterized by haste ignitability (*Table 4*). Physicochemical biomass properties varied. The variation relates to biomass quantity, quality, moisture content and aeration, which influence flammability. For instance, biomass quantity increases combustion but likely enhances sustainability as larger fuel quantities take longer to burn. Moisture content is the main influencer on ignitability, and species with higher moisture contents took longer to ignite and burn slower (Simpson et al. 2016).

Table 4. Fidelity level value and properties of commonly reported energy tree species

Species name	Properties category	Citation for properties	Fidelity level (%)
Acacia seyal	Combustibility	31	83%
Acacia nilotica	Sustainability	27	69%
Vachellia tortilis	Ignitibility	17	56%
Acacia mellifera	Ignitibility	17	36%
Albizia amara	Sustainability	8	34%

4 CONCLUSIONS

The study results prove that local people exploit their traditional knowledge to select energy species based on their properties. Among the most important local species used for energy production were *Acacia mellifera*, characterized by ignitibility, and *Acacia nilotica*, characterized by sustainable combustion. Based on their properties, these species are considered favourable for all biomass energy consumers in the study area, including domestic households, bakeries, and brick producers. Consequently, the interest in these species is enormous and may lead to degradation or extinction. Strengthening the results of this study with further research and laboratory verification of the characteristics of the selected species is required. Rehabilitating degraded species in energy plantation and agroforestry programs should be a priority.

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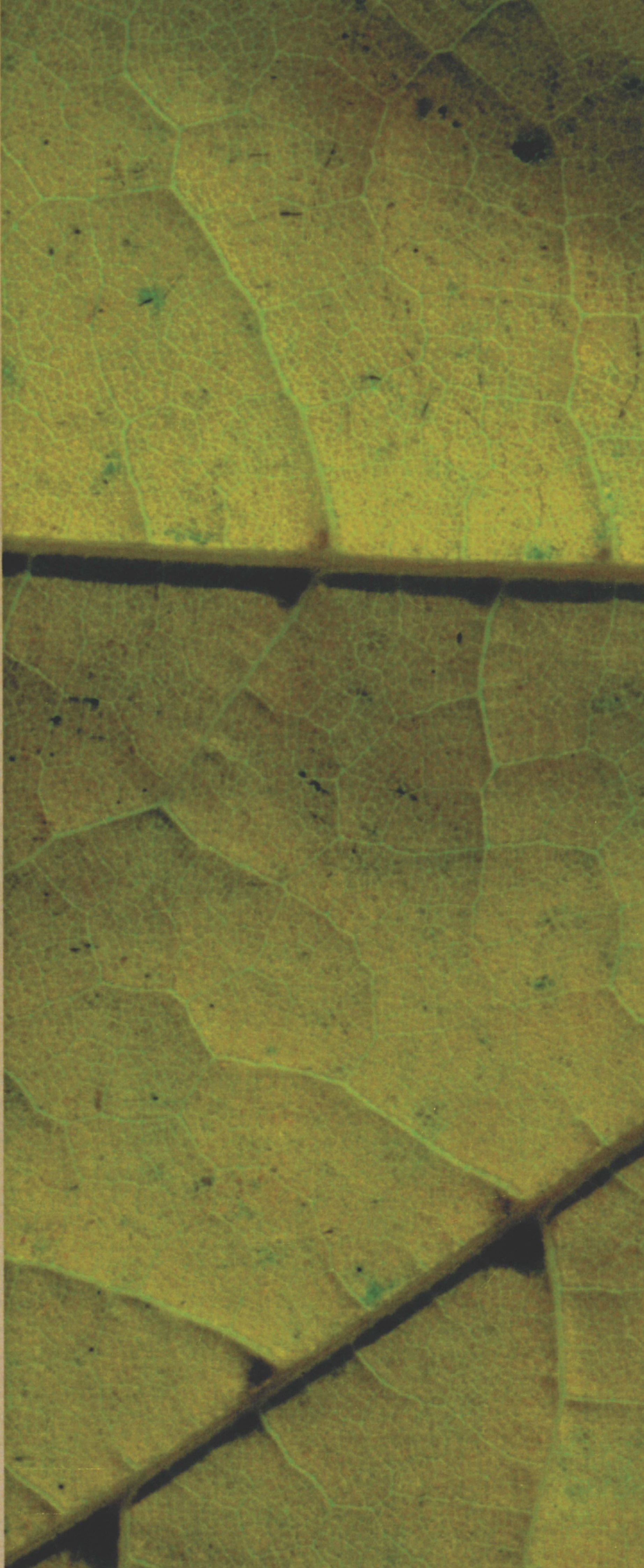

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