

**BIOMASS RESIDUES FROM FOREST HARVEST OR INDUSTRIAL PROCESSING
– WASTE OR HIGH - VALUE RENEWABLE RAW MATERIALS?**

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Abstract

The paper presents the results of experimental research performed with native hornbeam and Robinia stem - and branch wood of forest origin as well as property - modified wood from poplar of forest and plantation origin.

Results show higher density and strength properties of different branch assortments, enabling native wood material application in special higher utilization demands.

In the case of lower stem wood properties of forest or fast-growing plantation poplar (low density, strength, moisture related behaviour, durability), quality improvement due to wood impregnation shows amazing modified new properties, making possible utilizations even under higher

moisture conditions or strength as well as hardness demands. First applications in flooring material or moist-room equipment have been tested or are under development. Especially the application of thermal-treatment, combined with wood compression or the use of renewable impregnation agents from regrowing plant materials (liquids with higher content of phenolic compounds from pyrolysis-thermal treatment or hydro-thermal carbonisation processes) enhance the possibility of eco-friendly methods of wood modification or wood impregnation.

Key words: harvest residues; fast growing plantation; process residues; wood properties; wood modification.

INTRODUCTION

The production and use of renewable biomass is - in frame of the present economical and ecological challenges, such as the limited fossil materials and energy sources, climate change, increasing demands for resources, environmentally critical production systems as well as waste disposal - a suitable environmentally friendly potential compared to fossil materials and energy. In this respect, biomass production on forest-, agriculture- or plantation sites has a lot of environmental advantages compared to non-renewable materials (FAO 2005, Rademacher et al. 2014).

Due to the increasing prices of worldwide soaring energy demand, more and more biomass is used for energy supply, with high influences on biomass and wood prices as well as on their availability. The amount of wood with properties adequate for higher value-use is limited. More and more wood assortments with higher wood properties are also used for energy, limiting the supply even more. During the last years the competitiveness of lower and medium price wood industry sectors have been weakened due to this development, requiring better political dispersal structures and better economical assortment standards (Gurau et al. 2011).

The availability of conventional wood sources, mainly stem wood, is also limited and not suitable anymore in the demanded quantity. Due to this development, investigations and processes have been engineered to make additional wood and suitable biomass assortments disposable for varying requirements (Rademacher et al. 2015). Possible sources for this can be:

- forest harvest residues (thinning/crown material, branches, bark);
- lesser used wood species with different properties and applications;
- fast growing plantation biomass and wood material;
- upper value usage of calamity wood, damaged wood, used wood;
- up-grading of wood assortments with lesser value by wood modification.

A higher use of up to now lesser used wood species can improve the biodiversity of traditional poor or monoculture forest stands. With respect to the changing climate this can reduce the danger of damaging monocultures and improve the growth and yield of those tree species which were suppressed in the past by the forest management and previous climate conditions and are better adapted to warmer climate, like oak, *Robinia* (or Black locust) or European chestnut.

But not only forest species with already higher native wood properties, but mainly lower growth, can enrich the wood market. Also the potential of fast growing plantation trees from short and medium rotation coppice systems, like poplar, willow or *Robinia*, will be needed to fulfill the demand of a larger supply of renewable raw material (Hornicek et al. 2015). These management systems show a potential of productivity, which is up to ten times higher compared to forests. The main problem in utilization of the mentioned assortments is the quality of wood, which is mainly low and not suitable for higher value demands. Due to these disadvantages, the application of these wood categories is actually restricted to energy or low-level uses.

Wood modification can help to improve the insufficient wood properties. Traditional wood protection, processed by impregnation of wood with biocides, is mainly limited to increase the wood durability, reducing or preventing the wood deterioration activity of wood decaying fungi or insects; further improvements of additional wood properties are not possible or possible only to a minor degree, because the relevant wood structure is widely unchanged by this process. In contrast to this, wood modification which works on the basis of structural changes of wood components, influences many wood properties, like moisture behaviour (humidity uptake, swelling/shrinkage), physical and elasto-mechanical properties as well as durability (Ermeýdan et al. 2012). In addition, the mainly toxic-free composition of wood modification agents leads to environmentally friendly process conditions and non-complex admission requirements. Not only toxic-free, but also sustainable and renewable production and application processes, using native solutions from plant growing components have been developed by MENDELU wood research group in Brno.

OBJECTIVE

The main objective of the present research was to evaluate additional wood sources and assortments of lesser or not used origin, like harvest or crown residues, lesser used wood species or fast growing plantations. Also the property improvement of low value wood qualities by wood modification and its positive influence on properties was investigated in order to show possible higher wood utilizations.

MATERIAL, METHOD, EQUIPMENT

Impregnation of poplar wood with liquid process residues from thermal-treatment (TT, 2 temperatures 180°C and 200°C), hydro-thermal carbonisation (HTC, 2 raw materials: Miscanthus [Misc.] and sawdust [Saw]) and phenol-components from beech wood pyrolysis process (Pyrol):

- volume swelling in 65% RH/ 20°C: 10 samples of 14 x 14 x 28 mm³ for each treatment;
- durability: 9 samples of 5 x 10 x 30 mm³ (Bravery Test) for each treatment; fungi: *Trametes versicolor*, decay 6 weeks (according to EN 113);
- production/use of liquid residues from thermal treatment (TT)-, HTC- and pyrolysis-process;
- impregnation of beech and poplar sets of samples using vacuum 20 kPa/ 1 hour;
- dilution: pyrolysis 1:10; 1:2; original (1:1 = 100%); TT and HTC concentrated 10:1;
- conditioning, drying, volume/ weight, leaching, bulking measurement following standards.

Hornbeam/Robinia stem- and branch wood investigations: Table 1 shows the investigated wood material of 2 hornbeam (80–90 yrs.) and 3 *Robinia* trees (55–90yrs.), taken from several heights (every 2.5–3 meters) and radial-gradients (bark/cambium to pith; comp. Fig. 4). Thus results can be determined not only as species or tree average, but also for height and diameter related dependency.

60 cm long boards were cut from each section of each tree of both species. The diameter of the branches (16–35 yrs.) varied from 5 to 15 cm. For investigations mainly bigger branches were used due to higher sample demands. The samples for density measurement [ρ_0] were dried at 103°C until weight constancy. Before mechanical tests the samples were conditioned in the climate chamber at 20°C/65%RH, differences to standard climate of 12% moisture content were corrected according to Czech standard ČSN 49 0116 (determination of modulus of elasticity - MOE from static bending) and ČSN 49 0115 (measurement of bending strength – modulus of rupture [MOR]):

$$MOE_{12} = \frac{MOE_w}{1 - \alpha(w - 12)} \quad MOR_{12} = MOR_w[1 + \alpha(w - 12)]$$

$\alpha_{MOE} = 0.01$; $\alpha_{MOR} = 0.04$: correction coefficient (for all wood species); w = moisture content

Specimens of 14x14x210 mm³ were used for the bending test in radial direction. The dimensional parameters were measured by a digital caliper and weighted with a laboratory scale. The 3 point bending test was carried out using Zwick Z050 universal testing machine.

The microscopic investigations were carried out at 55–90 yrs. old stem wood and 15–20 yrs. old branches. The samples were stained with safranin; size measurements of vessels (hornbeam > 14 μ m diameter, *Robinia* > 50 μ m) and evaluation of the porous structure were carried out using ImageJ.

Viscoelastic-Thermal-Compression (VTC): The wood material used for VTC-investigation was plantation grown poplar clone Max4 (*Populus nigra* x *Populus maximowiczii*; 12 boards from basic stem logs of 8 trees) from the Pardubice region, Czech Rep. All samples were prepared from split and debarked logs and dried under room conditions. Dimensions of samples were 4x70x550 mm³ (r+t+l) for the first compression group (VTC1) and 6x90x550 mm³ for the second group (VTC2), 12 pieces each. The samples were conditioned before treatment in a conditioning chamber at 65% RH and 20°C.

The process of VTC was carried out in a pressurized vessel equipped with a heated hydraulic press (Kutnar et al. 2008). The temperature during compression was 170°C for 2.5 minutes, which was increased to 200 °C for 4 minutes. Compression ratio depended on the group. The first group (VTC1) was compressed from an initial thickness of 4 mm to 2 mm, in the second group (VTC2) thickness change was from 6 mm to 2 mm. After cooling the samples were conditioned in a conditioning chamber with 65% RH and a temperature of 20°C.

Measurements of physical and mechanical properties were carried out by non-destructive methods; each treatment group consisted of 12 replications of original size (see above), including all knots and other failures in order to show semi-practical material quality for future utilization. EMC (EN 13183-1) and MOE (Fakopp 2D ultrasonic timer) were measured after conditioning of all samples in 65% RH and 20 °C compared to dried samples in 103°C (density [ρ_0]). MOE was measured in several areas without knots and other failures by means of each of 12 full size samples per treatment, using a

distance of 100 mm between source and target sensors and fitting to the gap between knots and other failures.

Table 1

List of investigated materials and markings; M = microscopic investigations

Mark	Species	Age	Type	Samples
H35	Hornbeam	35	branch wood	6 samples (4x M)
H80	Hornbeam	80	stem wood	5 boards, 16 samples (4x M)
H90	Hornbeam	90	stem wood	4 boards, 29 samples,
R16	<i>Robinia</i>	16	branch wood	6 samples (2x M)
R20	<i>Robinia</i>	20	branch wood	3 samples (2x M)
R33	<i>Robinia</i>	33	branch wood	8 samples
R55	<i>Robinia</i>	55	stem wood	3 boards, 19 samples
R60	<i>Robinia</i>	60	stem wood	3 boards, 16 samples (2x M)
R90	<i>Robinia</i>	90	stem wood	4 boards, 27 samples (2x M)
Max4	Plant. Poplar	6	stem wood	8 trees, 4x12 boards, 48 samples
Pop	<i>Pop. tremula</i>	70	stem wood	1 tree, 1 board, 9-10 samples each

RESULTS AND DISCUSSION

Harvest and process residues as chemical sources for wood impregnation

Volume swelling in 65% rel. humidity/20°C was reduced from 6.5% in untreated poplar to 5% in wood impregnated with process residues of thermal treatment (TT) using 180°C or 200°C resp. Process using HTC-liquids of Miscanthus- (Misc.) or Sawdust- (Saw) from Hydrothermal Carbonisation (HTC) showed reduction to 3.0-3.5% and pyrolysis liquid treatment (Pyrol-Liqu.) even 2.5% (Fig. 1a). The mass loss due to decay of native beech (30-35%) and poplar (40-50%) was reduced to 2% in the case of pyrolysis treatment and to 4% in the case of TT-treatment, depending on wood species, impregnation method, concentration and leaching process (Fig. 1b). Attendant bulking tests and UV scans prove the high inclusion of phenolic compounds into cell walls (Rademacher et al. 2014; 2015).

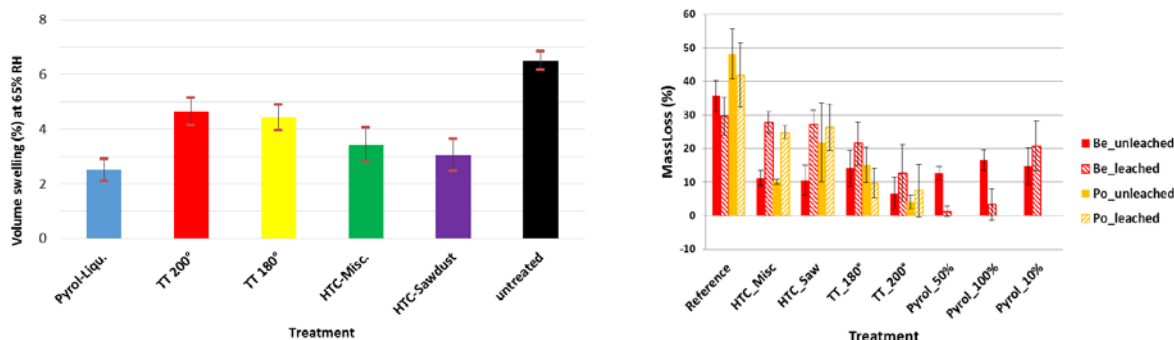


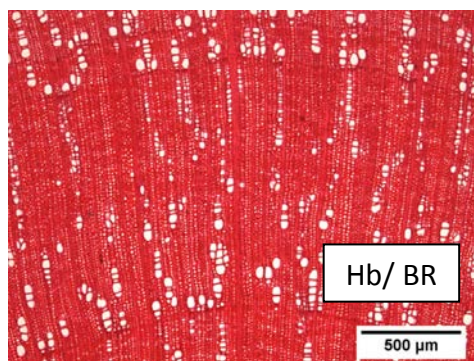
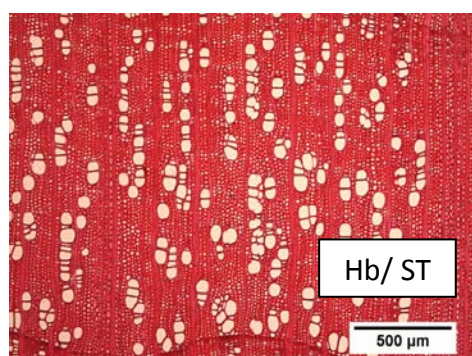
Fig. 1.

Fig. 1a: Volume swelling of poplar wood.

Fig. 1b: ML of pyrolysis-liquid impregnated poplar.

Branch - and Crown Wood utilization - Examples: Hornbeam and Robinia

Microscopic investigations: Hornbeam branches show, compared to stem wood, much wider rows of vessel groups, visible in radial-neighbourhood orientation with a lower size of single vessels. The total area of larger pores (> 14 µm in diameter) is clearly lower in the case of hornbeam branches (Tab. 1; Fig. 2 + 3). Compared to stem wood fibers, the cell wall thickness of branch wood fibers was lower, so the general density of hornbeam branch wood was only slightly lower than of stem wood.



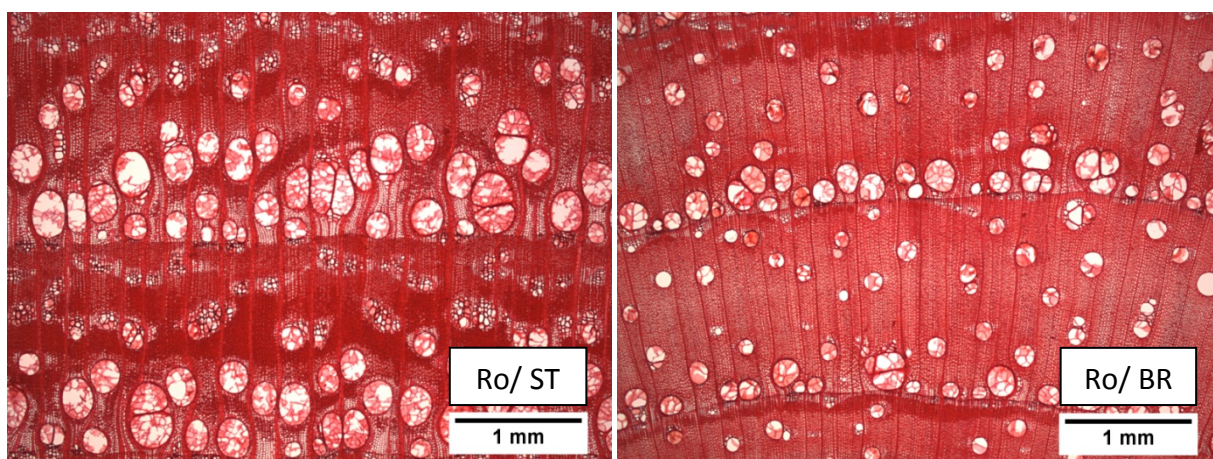


Fig. 2.

Cross sectional transmitted light microscopy images of forest grown hornbeam (Hb) and Robinia wood (Ro) of stem wood (ST, left) and branch wood origin (BR, right).

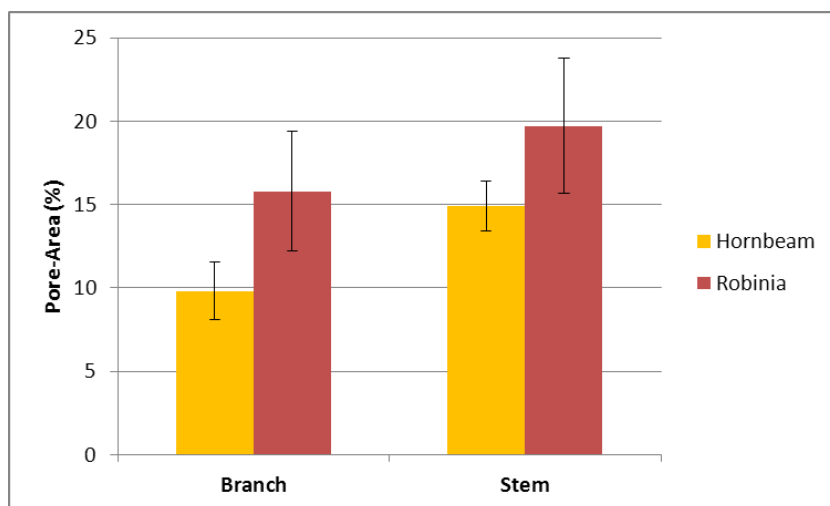


Fig. 3.

Total pore area of Hornbeam (pores > 14 μm) and Robinia (> 50 μm) of stem and branches.

In the case of *Robinia*, the situation was similar, but 20% lower porous system (> 50 μm in diameter) in branch wood resulted in a dominant effect on higher density compared to stem wood (Tab. 2; Fig. 3).

Table 2
Image processing analysis of pores in hornbeam (Hb) and Robinia wood (Ro) (ImageJ): comparison of branch wood and stem wood: mean values, var. coeff. [%], brackets]. Included lumen diameter >14 μm in the case of hornbeam and >50 μm in the case of Robinia.

Spec	Pores/mm ²		Mean pores lumen diameter [μm]		Mean area of pores lumen [μm ²]		Percentage of total lumen pores area [%]	
	B	S	B	S	B	S	B	S
Hb	131 (11.6)	136 (18.8)	30.8 (4.0)	37.7 (5.9)	745 (7.9)	1119 (12.2)	9.8 (17.5)	14.9 (10,1)
Ro	9.5 (26.0)	7.0 (18.8)	146.5 (10.3)	189.2 (1.0)	17037 (20.2)	28118 (2.1)	15.8 (22.9)	19.7 (20.6)

Wood density: In hornbeam the variability in density of stem wood is low, values differ between 740–790 kg·m⁻³ in 90-year-old tree and 730–815 kg·m⁻³ in 80-years-old tree with focus of higher values of basic height and unspecific radial position of maximum values. In branch wood of

hornbeam the density is similar, only about 6% lower (ca. 615 kg·m⁻³) compared to average values of stem wood (ca. 760 kg·m⁻³ [Fig. 4 + 5]).

Tree	Bark	1	2	3	4	5	6	7	8	9	Pith	
H90	↑ Height	782	755	755								
		758	774	771	763							
		751	767	760	757	744	751					
		765	781	779	799	797	760	779	757	780		
		789	790	779	767	747	767	772	776	734		
H80	↑ Height	732	726	727								
		738	734	766	719							
		772	778	783	760	737						
		775	793	794	813	814	805					
R55	↑ Height	719	671	705	702	699						
		643	675	723	717	716	735					
		685	684	695	735	706	725	768	760			
R60	↑ Height	607	622	660	693	710						
		574	630	622	630	648	627					
		608	627	651	665	679	713	747				
R90	↑ Height	660	681	724	742							
		694	713	688	735	757	731	767				
		653	685	688	719	741	702	671	698			
		693	667	677	669	685	735	720	745	770		

Fig. 4.
Wood density (kg·m⁻³) of stem wood of 80 and 90 yrs. old hornbeam trees (H) and of 55, 60 and 90 yrs. old stems of Robinia (R). The darker the green, the higher the value. Red: interpolated values due to missing or damaged sample.

All *Robinia* stem wood samples show the highest wood density in the center of the stem disc. Compared to the inner wood of upper stem sections (630–750 kg·m⁻³), basic stem sections show the highest density (750–770 kg·m⁻³), whereas mainly in younger wood sections near the bark and cambium densities are much lower (570–700 [max. 720] kg·m⁻³; comp. Fig. 4). Reasons can be higher growth in former juvenile period of trees, where supply with light and other growth-limiting factors was better due to lower growth competition of smaller trees. In the case of ring-porous trees like *Robinia*, this leads to a higher percentage of heavier and denser late-wood. Also the accumulation of extractives and heartwood components in older center wood cells, which can be in the case of *Robinia* heartwood up to 10%, can lead to higher weight and increased density (Rademacher et al. 2014).

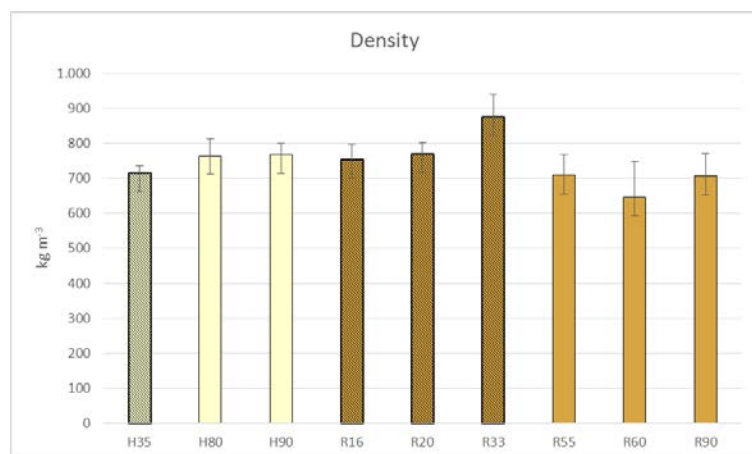


Fig. 5.
Wood density (kg·m⁻³) of stem wood of 80 and 90 yrs. old hornbeam trees (H, beige) and of 55, 60 and 90 yrs. old stems of Robinia (R, brown) as well as of 16 – 35 yrs. old branch material (shaded) in kg·m⁻³.

Compared to the density in *Robinia* stem wood, the values in branches were higher: The average of all stem wood samples was about 650–710 kg·m⁻³, whereas branch wood showed density of about 750–880 kg·m⁻³, with the maximum around 950 kg·m⁻³, exceeding even highest values in Hornbeam (Fig. 5).

Mechanical strength: Due to more homogenous wood structure, hornbeam branch wood has – in spite of slightly lower wood density - similar or even higher MOR and MOE compared to stem wood. *Robinia* shows strong dependency on MOR on branch wood density (Fig. 6).

While the density shows – in the case of all species-sorted values - no (all stem wood and hornbeam branch wood samples) or only low relationship (MOR of *Robinia* branch wood) with MOR and MOE resp., the tree- and height-related values have much higher regression coefficients of up to r² = 0.9 (Fig. 7). Here the interesting trend of equal or even higher MOR and higher MOE with lower densities

in the upper stem heights is visible (Fig. 7). Consequently, *Robinia* branches deliver a wood material with the maximum amount of material strength, exceeding even the highest MOR values of stem wood (ca. 165 MPa) by about 15%.

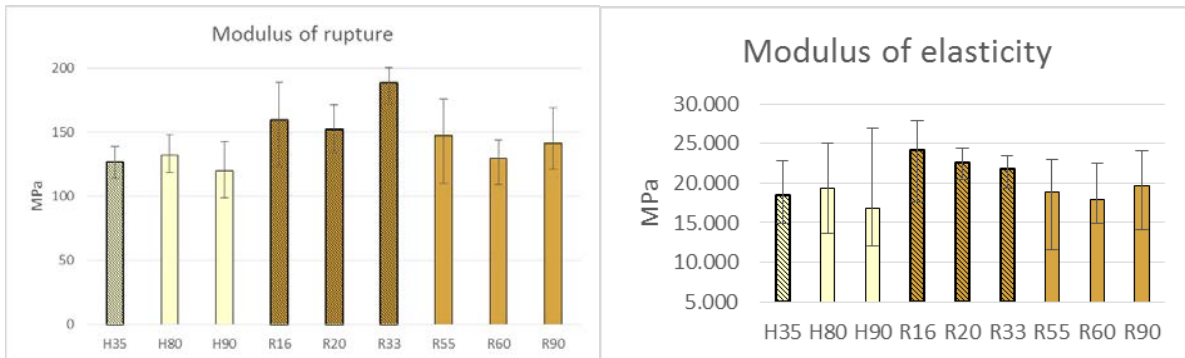
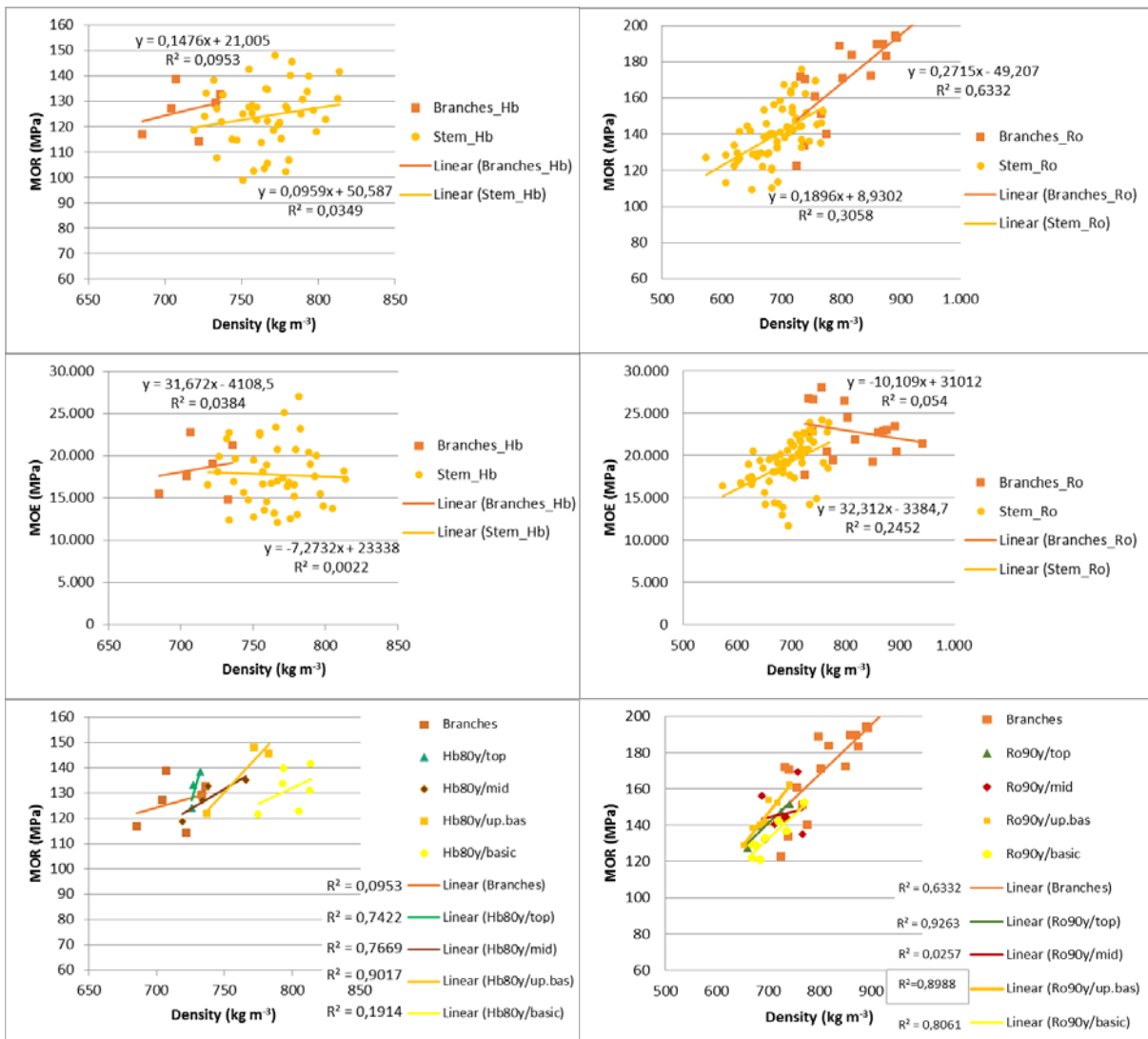


Fig. 6.

Modulus of rupture (left) and modulus of elasticity (right; MPa) of stem wood of 80 and 90 yrs. old hornbeam trees (H, beige) and of 55, 60 and 90 yrs. old Robinia trees (R, brown) as well as of 16–35 yrs. old branch material (shaded).



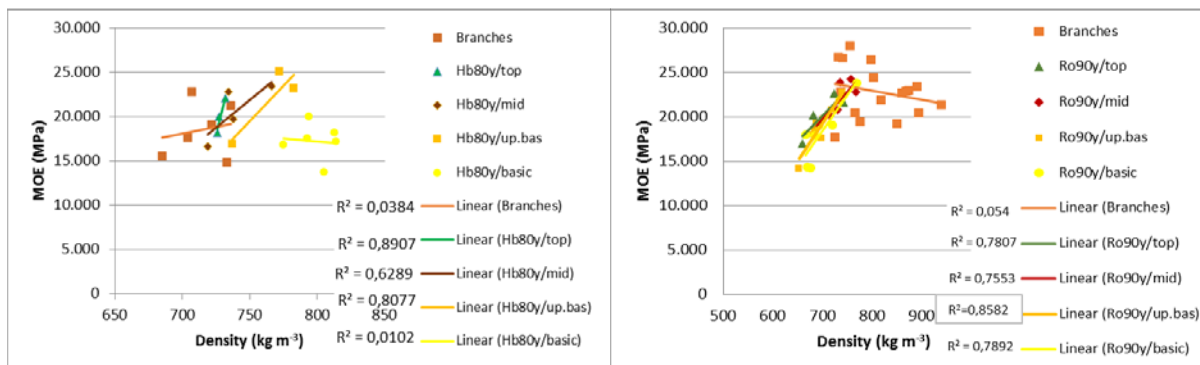


Fig. 7.

Modulus of rupture (MOR) and modulus of elasticity (MOE; MPa) of 55-90 years (y) old stem wood (top-basic) and 16-35 years old branches from hornbeam (Hb [left]) and Robinia (Ro [right]). Upper 4 graphics: correlation and regression analysis of all ages and stem heights, lower 4 graphics of selected single tree compartments: branches, stem wood in top, middle = mid, upper base = up.bas., and basic height position.

Viscoelastic thermal compressed wood from fast growing poplar plantations

Density ratios after compression of materials were 1 : 2.3 : 2.9. Significant decrease of EMC was observed in the case of both treated materials (Fig. 8), showing similar behaviour for both densification ratios. The same improvement is visible (Fig. 8) in the case of MOE with three times higher values of both compressed materials compared to control. Higher densities of materials – native as well as compressed – result usually in higher mechanical properties (Kutnar et al. 2008). Due to high variability of MOE for semi-practical sized samples no differences could be determined in this study between varied intensities of densification (Hornicek et al. 2015).

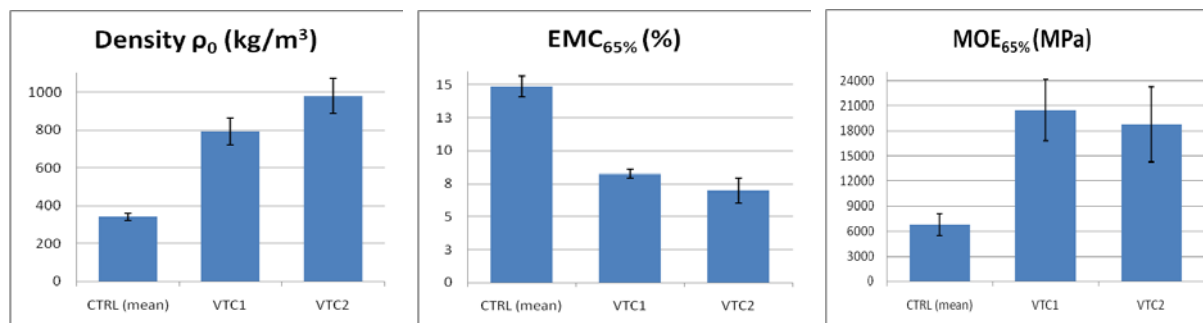


Fig. 8.

Selected properties of density [ρ_0], EMC_{65%RH} and MOE_{65%RH} in VT-compressed plantation poplar.

CONCLUSIONS

The results obtained within the present research demonstrate that solid or liquid harvest or process residues from forest wood resource as well as thinner materials from SRC can provide a wide field of additional wood utilizations. Examples show that native properties of crown and branch material, as well as thermal, mechanical or chemical improved wood properties deliver new materials with new properties, replenishing or exchanging the limited amount of native wood with higher values.

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