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Selected properties of particleboards made of different cultivars of apple wood particles

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Abstract: *Selected properties of particleboards made of different cultivars of apple wood particles.* The aim of the research was to determine the density of wood and the possibility of using particles from various cultivars of apple wood for the production of particleboards. The following apple cultivars were used in the research: Gala (*Malus domestica* Borkh), Prince (Red Jonathan Cltv.), Golden Delicious (*Malus domestica* 'Golden Delicious' Cltv.), Champion (*Malus domestica* 'Szampion' Cltv.). As part of the work, three-layer particleboards were produced in laboratory conditions from particles made from branches, and selected physical and mechanical properties of the obtained boards, as well as the wood density of the branches themselves, were examined. The tests confirmed the existence of differences between the density of the tested apple wood, as well as between the properties of the produced particleboards. The research also showed the possibility of producing boards for the furniture industry using wood from the mentioned apple cultivars.

Keywords: particleboard, alternative raw material, apple tree, mechanical properties, physical properties

INTRODUCTION

In today's world where sustainability is becoming increasingly crucial, finding innovative ways to use waste is becoming a priority. In the context of this unique situation, it is worth focusing on the search, for alternative raw materials. They will not only allow effective waste reduction but also contribute to the development of the industry. The wood industry plays a significant role in the economy of many countries. In 2018, the global felling of industrial wood amounted to 2,028 m^3, which is 5.2 per cent more than in 2017 (1,826 million m^3) and 8.9 per cent more than in 2014 (FAO 2019). The drastic increase between 2014 and 2018 proves the volume of demand and the need for rapid development of the wood industry. Poland, next to Sweden and Finland, is responsible for the greatest impact on the increase in the production of industrial roundwood. The increase in production in 2017 compared to 2012 was evaluated by almost 10 per cent, which is an increase of over thirty million m^3 (Kudełko 2016). One of the main challenges we face is the effective management of waste from this sector.

Fruit farming plays a key role in the economy of many regions around the world. The area under orchard cultivation in Europe in 2017 was as much as 1.73 million hectares (Leonte et al. 2020). One of the most important products from this sector is apples. Apples are the most harvested and exported fruit in Europe. Poland, Italy and France are the leading producers of this fruit, on the continent (Tougeron and Hance 2021; Dyjakon et al. 2016; Shuai and Guyou 2023). Traditionally, the waste is composted or burned, which generates not only economic losses but also a negative impact on the environment in the form of greenhouse gas emissions and air pollution (Dyjakon et al. 2016; Romański et al. 2014). In recent years, attention has been paid to the possibility of using apple tree branches, which are one of the frequently generated wastes in orchards, as a raw material to produce particleboards (Auriga et al. 2019; Kowaluk et al. 2020; Lykidis et al. 2014).

Other studies conducted on the use of alternative lignocellulosic materials concerned, among others, corn cobs (Akinyemi et al. 2016; Atoyebi et al. 2019), rapeseed and hemp pomace (Nikvash et al. 2010), cassava stalks (Aisien et al. 2015), pineapple leaves (Tangjuank 2011), peanuts (Güler and Büyüksari 2011), plum wood (Kowaluk et al. 2020; Auriga et al. 2019), cherry wood (Lykidis and Grigoriou 2014), coffee husks (Bekalo and Reinhardt 2010).

AIM AND SCOPE

The aim of the work was to investigate whether the apple cultivar affects the physical and mechanical properties of the three-layer particleboard produced from it. An additional goal was to investigate whether waste wood from the annual cutting of apple tree varieties: Gala, Prince, Golden Delicious and Champion, is suitable for use as an addition in the form of lignocellulosic mass, in the mass production of particleboards. The scope of work included the estimation of the density of the mentioned wood as well as the production of particleboards from tree branches in laboratory conditions. The investigation of the differences in the selected physical and mechanical properties between apple tree wood varieties was completed and the achieved results have been referred to the properties of reference boards made of pine wood particles.

MATERIALS AND METHODS

To produce particleboards, particles obtained from waste wood of four cultivars of apple trees were used: Gala (*Malus domestica* Borkh) hereafter called GA, Prince (Red Jonathan Cltv.) hereafter called PR, Golden Delicious (*Malus domestica* 'Golden Delicious' Cltv.) hereafter called GO, Champion (*Malus domestica* 'Szampion' Cltv.) hereafter called CH, as well as industrial pine (*Pinus sylvestris* L.) particles, hereafter called 0. Apple wood waste resulting from annual maintenance work was collected from an orchard located in the Masovian Voivodeship, near the town of Wilga. It should be noted that all apple trees, grew on the M9 base. The most notable features that may affect wood, are growth restriction and strong branching (Karlidağ and Aslantaş 2014).

The material used in the research was waste apple wood in the form of branches, with a diameter of 10 to 50 mm. This is important, due to the share of bark contained in the branches. They were then cut in length into smaller pieces (ca. 50 mm). The next stage was to transform them into particles, using a laboratory cutting machine with a knife shaft. After drying in a laboratory chamber dryer under 103°C to achieve a moisture content of about 2-4%, the particles were divided into the core layer and surface layers fractions, each of which passed through separate sieves, with different mesh diameters. For the outer layer, the particles passed through holes with a diameter of 2 mm and settled on a sieve with holes with a diameter of 0.25 mm. Accordingly, for the core layer, the particles were larger and were sieved through an 8 mm diameter mesh and remained on a 2 mm diameter sieve. The fraction share of the produced particles has been characterized, and the results have been displayed in figure 1.

The goal of laboratory production was to produce boards with a nominal thickness of 16 mm and a nominal density of 700 kg/m^3. The process of creating boards began with the preparation of the adhesive mass. The main ingredients were urea-formaldehyde (UF) Silekol S-123 resin of 65% solid content (Silekol Sp. z o.o., Kędzierzyn—Koźle, Poland), distilled water and a hardener in the form of ammonium sulfate $(NH_4)_2SO_4$ 50% water solution. The proportions of the adhesive mass solution were 100:4:5 parts by weight for resin, hardener solution and water, respectively. No hydrophobic agent has been added. The mass share of face layers was 32%. Pressing conditions included the following values: temperature 200°C, pressing time 20 s/mm of nominal panel thickness, maximum unit pressure 2.5 MPa and have been applied in a hydraulic press (AKE, Mariannelund, Sweden). There were produced three boards, with dimensions of 320x320 mm^2 from each apple tree wood cultivar. Three reference boards were also made of pine wood, where production parameters were the same as those of apple tree boards. The produced boards were air-conditioned at 20°C ±1°C and 65%±2% relative humidity for 7 days for weight stabilization before testing.

After the boards were manufactured, a series of tests were conducted in accordance with commonly used standards (EN), whenever available. The tests carried out included: examining the density of the wood material used for the inner and outer layers of the boards and the wood used for the tests, thickness swelling (TS) and water absorption (WA) after 2 hours and 24 hours (EN 317), internal bond (IB) test performed using the standard EN 319, modulus of elasticity (MOE) and modulus of rupture (bending strength) (MOR) (EN 310), screw withdrawal resistance (SWR) (EN 320), examining the mass share of the internal and external layers, density (EN 323) and density profile using GreCon DAX device (Fagus-GreCon Greten GmbH and Co. KG, Alfeld/Hannover, Germany), based on x-ray technique, with sampling step 0.02 mm, measuring speed 0.1 mm/s. The mechanical tests were performed on a computer-controlled universal testing machine (Research and Development Centre for Wood-Based Panels Sp. z o.o. Czarna Woda, Poland). For all measurements excluding density profile, as many as 10 samples were used from every tested variant (every investigated apple tree wood). For density profile measurement, 3 samples of each variant have been tested and after initial evaluation one representative plot has been selected for final evaluation.

The results, except for the wood density, density profile and particle bulk density, have been evaluated to show on the plots the average values and the standard deviation as error bars. The statistically significant differences between the achieved average values, wherever applicable, have been distinguished based on ANOVA analysis.

RESULTS AND DISCUSSION

The fraction share of the particles used for particleboard production has been displayed in figure 1. As can be seen, in the case of particles used for face layers (figure 1a), the biggest difference is for reference particles when compared to the particles produced from apple tree wood. In the case of reference particles, there is a higher amount of fine fractions, especially 0.25 and below. For reference particles of face layers, the entire fractions share is in general moved to the smaller fractions. The same remark can be drawn for core layer particles (figure 1b). Then after analysing the core layer particles made of apple tree wood, it can be found, that CH particles are the only, ones that have a higher amount of smaller fractions, and these are more similar to reference particles fraction share.

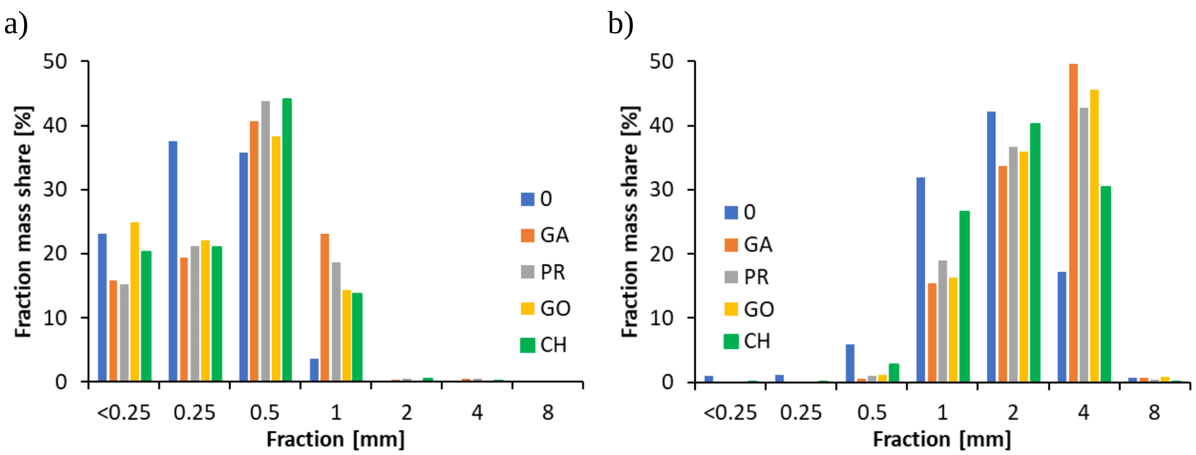

Figure 1. The fraction share of the particles for face layers (a) and for core layer (b)

Figure 2 shows the density differences between the materials for the inner layer (CL), outer layer (FL) and the wood used for testing. The most important result in the chart below is the relationship between the density of wood and the density of individual layers. The higher the wood density, the higher the density of FL and CL. It is also important to note, that the internal and external density varies depending on the cultivar. The Gala cultivar has the highest density for CL (320 kg/m^3), although the density of GA wood is 670 kg/m^3. A comparable situation is with the CH particles, where the wood density for these boards was the highest (720 kg/m^3), and the density of the CL layer was 250 kg/m^3. This was the lowest result among all apple varieties. It should be also pointed, out that in general, the density of apple tree wood is significantly higher than the reference wood. The results suggest that the properties of the wood used from apple varieties may affect the density and the remaining features of the produced boards. That remark has been confirmed by Kowaluk et al. (2020) by characterization of raw materials and panels produced from apple and plum pruning.

Figure 3 and figure 4 show water absorption and thickness swelling after 2 hours and 24 hours, respectively. The results from the mentioned figures indicate, that all apple varieties have remarkably related results to each other. Water absorption ranges between 58% and over 64% after 2 hours and between over 68% and almost 74% for results after 24 hours. It can also be noticed that all apple boards have lower water absorption, than the reference board (0), which results were 79% after 2 hours and over 87% for 24 hours. This result indicates, that apple trees can be a good addition to the production of boards, which will reduce water absorption and increase their water resistance, e.g. for boards produced for kitchen countertops. However, Nikvash et al. (2010) found, that the water absorption for particleboards made of selected alternative raw materials, like bagasse, canola and hemp, is higher than for reference panels. The statistically significant differences have been found for reference samples when compared to remaining, and for GA samples when referred to remaining after 2h and 24h of soaking, respectively.

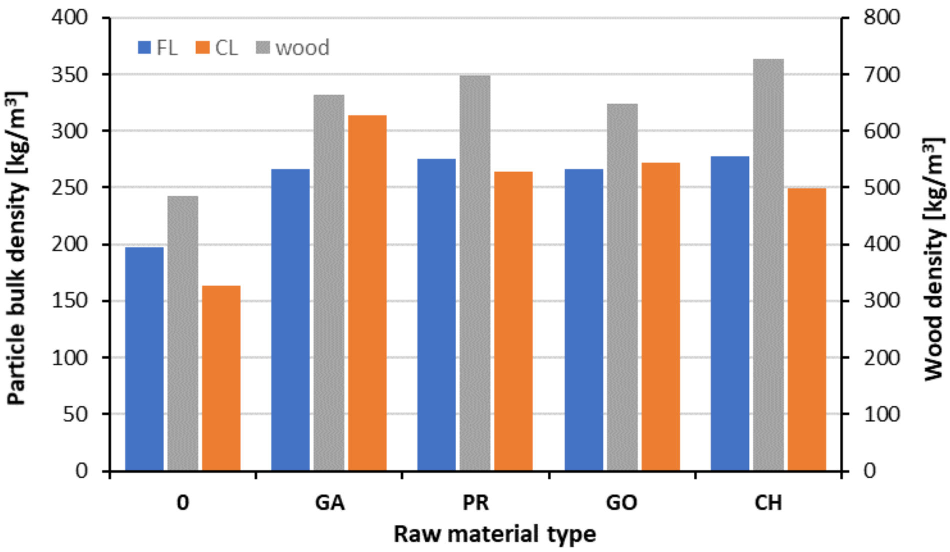

Figure 2. The bulk density differences between materials for the inner layer (CL), outer layer (FL) and density of wood used for testing

The results in figure 4, do not coincide with the results in figure 3. Despite lower water absorption for apple boards, their thickness swelling is higher than in the reference board (26%, and 31%, respectively for 2h and 24h of soaking in water), especially for GA varieties (33%, 44%) and GO (39%, 44%). The PR and CH boards have water absorption results between the results for the reference boards and between GA and GO. Such differences in swelling might be caused, by too many free spaces between the particles in the middle layer or weaker bonding between the inner and outer layers. However, it should be mentioned, that in the case of apple tree wood, there is a correlation between the thickness swelling and density of wood. It has been found, that the panels made of lower-density wood have a higher thickness swelling. It is due to the higher densification of wood particles during panels production, to achieve the nominal density. The particles, which were more densified, tended to swell in thickness more. The main and most important feature of all boards is that all apple varieties remain above the maximum swelling for P3-type particleboards mentioned in EN 312.

According to Kowaluk et al. (2020), the particleboards produced of higher density raw material, have lower thickness swelling.

The statistically significant differences have been found for reference samples when compared to remaining, for GO and CH after 2h of soaking, when referred to remaining samples, as well as for GA and GO after 24h of soaking when referred to remaining samples.

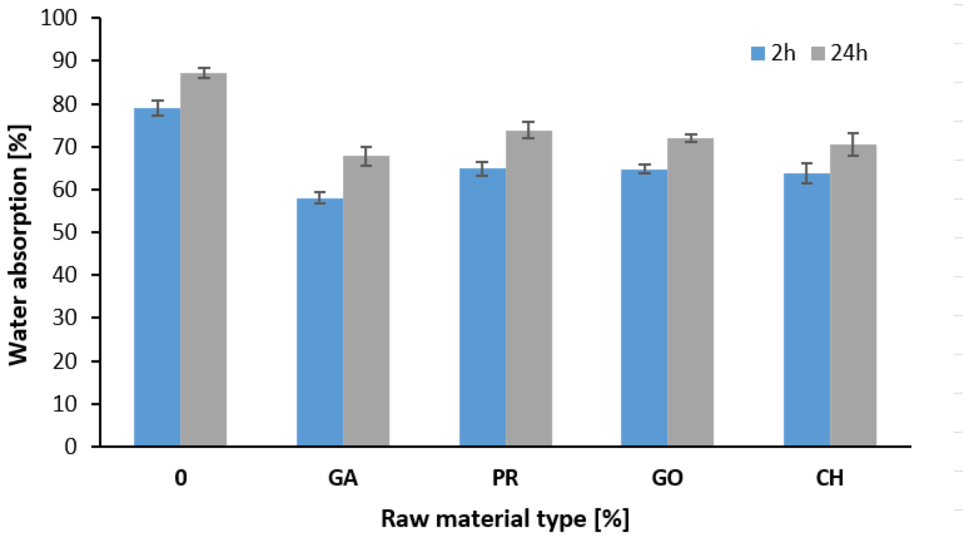

Figure 3. Water absorption of the particleboards made of different species of apple tree

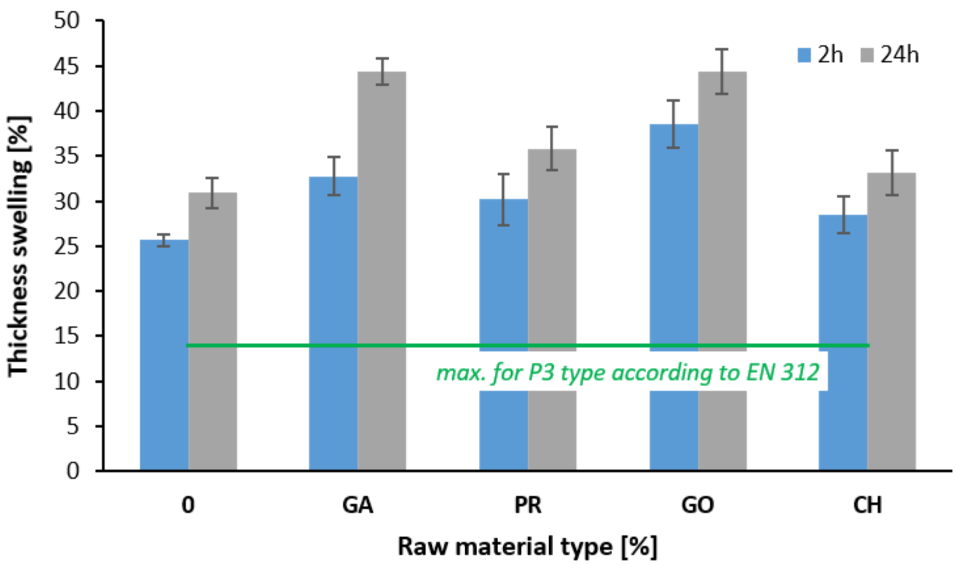

Figure 4. Thickness swelling of the particleboards made of different species of apple tree

Figure 5 shows the internal bond, which also indicates the tearing strength of the panels, i.e. their ability to resist forces, acting perpendicular to the plane of the panel. This is a measure of the material's internal consistency. The reference board (0) has the highest internal bond strength value (0.59 N/mm^2), which suggests that the pine wood used has stronger bonds between the particles. Apple cultivars show lower values. The CH cultivar has the lowest strength (0.33 N/mm^2). It is worth noting, that all apple varieties, except CH, exceed the minimum requirements for P2-type panels according to the EN 312 standard. This means that these boards are strong enough for specific applications, despite differences in strength.

Such a high internal bond of the reference panels can be the result of the low bulk density of the particles, as it has been shown in figure 2. The particles of low bulk density, when compressed in a mat to the exact thickness to reach the panel's nominal density, can give a higher amount of connections between the particles. This phenomenon has been confirmed also by Wronka and Kowaluk (2019), as well as by Pelc and Kowaluk (2023).

The statistically significant differences in average values of IB have been found for reference samples when compared to PR, GO and CH, and between GA when referred to GO and CH.

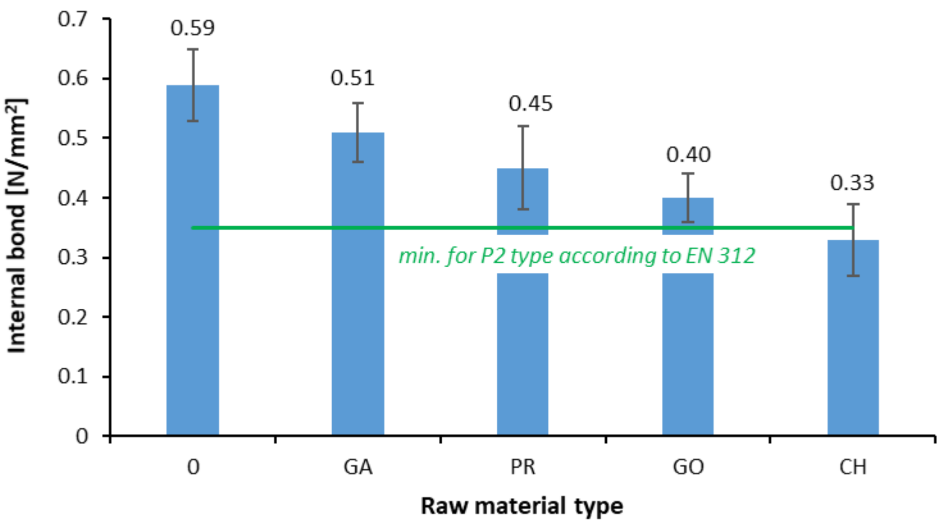

Figure 5. Internal bond of the particleboards made of different species of apple tree

Figure 6 shows the modulus of elasticity, which is a measure of a material's stiffness and its ability to deform under the influence of force. The reference board (0) has the highest modulus of elasticity (3403 N/mm^2). This indicates better bending resistance compared to boards from apple cultivars. The CH board has the highest modulus of elasticity (2353 N/mm^2), and the GA board, it is the lowest (1616 N/mm^2). The higher the modulus of elasticity, the more suitable the boards are for applications that require greater stiffness and resistance to bending loads. The most important feature of all boards is that all the apple tree wood varieties panels remain above the minimum modulus of elasticity given for P2-type panels according to EN 312.

The modulus of elasticity values, when referred to the bulk density of the particles, shown in figure 2, allows summarizing, that there is the influence of the core layer particles bulk density on the modulus of elasticity of the panels. It can be then concluded, that the modulus of elasticity grows when the bulk density of the core layer particles decreases.

Regarding statistical analyses, it can be found, that the statistically significant differences in average values of MOE have been found for reference samples when compared to remaining, and for CH when compared to GO and GA.

Figure 7 shows the modulus of rupture values, which determines the maximum tension, that a material can withstand before breaking. The reference board (0) shows the highest rupture modulus (14.6 N/mm^2), which is expected considering its higher modulus of elasticity. For apple tree cultivar boards, the CH board has the highest bending strength (10 N/mm^2), and the results of PR, GO and GA boards range between 7 and 8 N/mm^2. It should be noted that all apple tree wood boards have results below the minimum rupture modulus values given for P2-type panels according to EN 312.

The significantly lower modulus of elasticity and modulus of rupture of the panels made of wood from apple trees can be the fact, that the wood raw material comes from the branches, which are re-growing every few years. That means this wood can be recognised as a juvenile wood. Thus, according to Lindstrom et al. (2005), the mechanical properties of wood, such as modulus of elasticity and modulus of rupture can be lower, when referred to the mature wood, which is represented by reference panels.

The statistically significant differences in average values of MOR have been found for reference samples when compared to remaining, and for CH when compared to remaining samples.

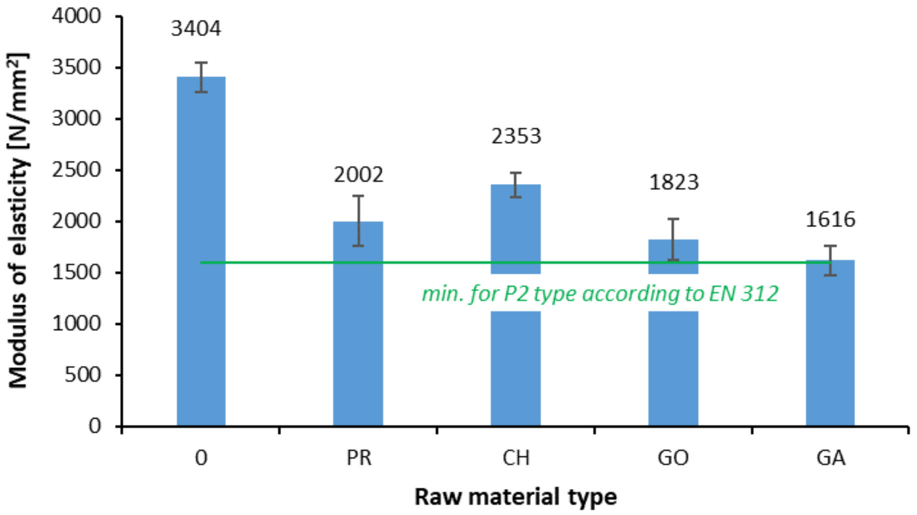

Figure 6. Modulus of elasticity of the particleboards made of different species of apple tree

Figure 8 shows screw withdrawal resistance, which is important for assessing the strength of connections. High resistance indicates better cohesion of the material and its ability to hold fasteners. The GA cultivar has the lowest resistance (111 N/mm), which may indicate lower density and better adhesion of particles in these samples. The PR samples had remarkably comparable results (138 N/mm) to the reference sample (143 N/mm). Boards made of GO (157 N/mm) and CH (159 N/mm) varieties showed the best particle connections and internal panel structure. The results indicate that apple varieties such as PR, GO and CH are suitable for use as additives in mass production. Their addition in the form of particles will increase the resistance of the boards, for pulling out connections such as eccentricities.

In the case of the analysed screw withdrawal resistance, there can be found the relation between SWR and the bulk density of the core layer particles is clear. The SWR rises with the core layer particles' bulk density decrease. This relation is so well visible since the core layer content (by weight) in the entire panel is 68%. The mentioned findings have been also confirmed by Wronka and Kowaluk (2022).

The statistically significant differences in average values of SWR have been found for GA when referred to remaining panels, for 0 when referred to GO and CH, as well as for CH when referred to PR.

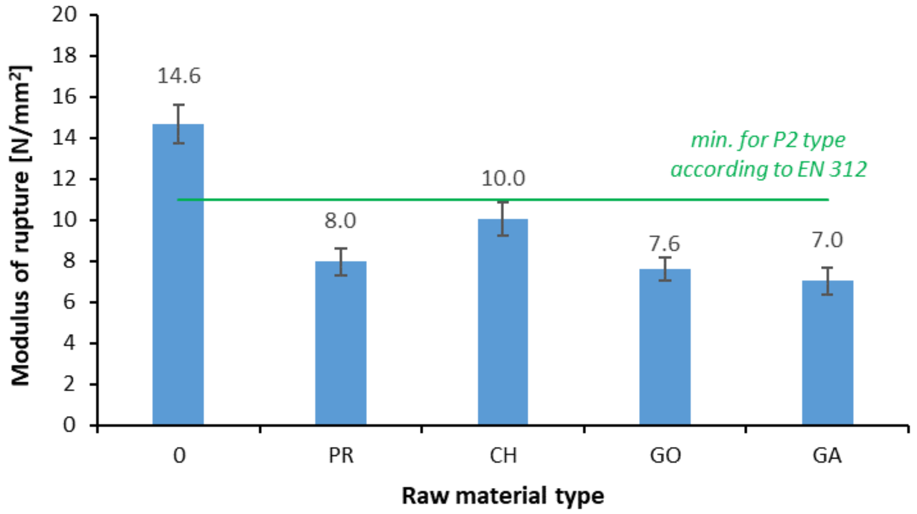

Figure 7. Modulus of rupture of the particleboards made of different species of apple tree

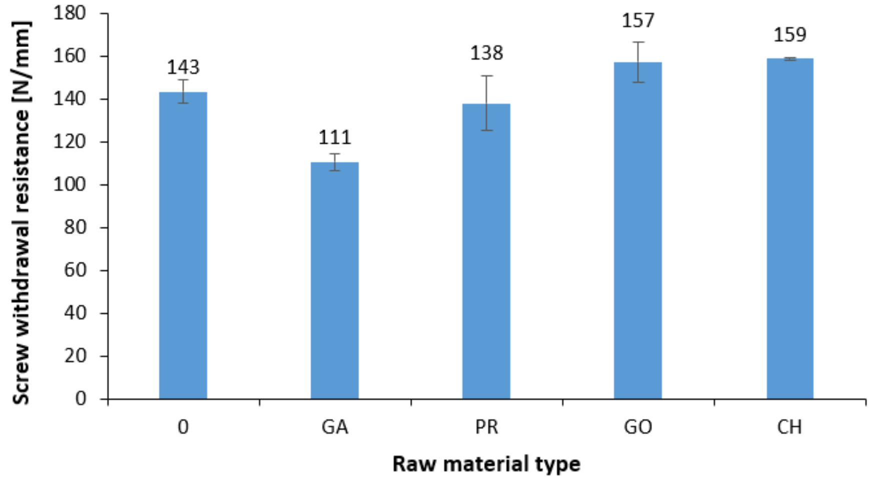

Figure 8. Screw withdrawal resistance of the particleboards made of different species of apple tree

Figure 9 illustrates the density profile of the particleboards. It reflects the distribution of material mass, throughout the entire cross-cut of the panel. All samples made of apple tree wood show similar density profiles, especially in the core, which may indicate a uniform distribution of particles during production (mat forming) and suggest, that the production process was controlled and repeatable for all apple varieties. This is also evidenced by the density of the panels. The planned nominal production density was 700 kg/m^3. The densities of the produced boards range from 697 kg/m^3 to 701 kg/m^3. The only difference between the apple tree boards and the reference board (0) is the lower density, in the outer layers for the reference board (0). This could have been influenced by the number of individual particle gradations used to produce individual boards. The mentioned differences in density profiles have been also found in the research of Kowaluk et al. (2020).

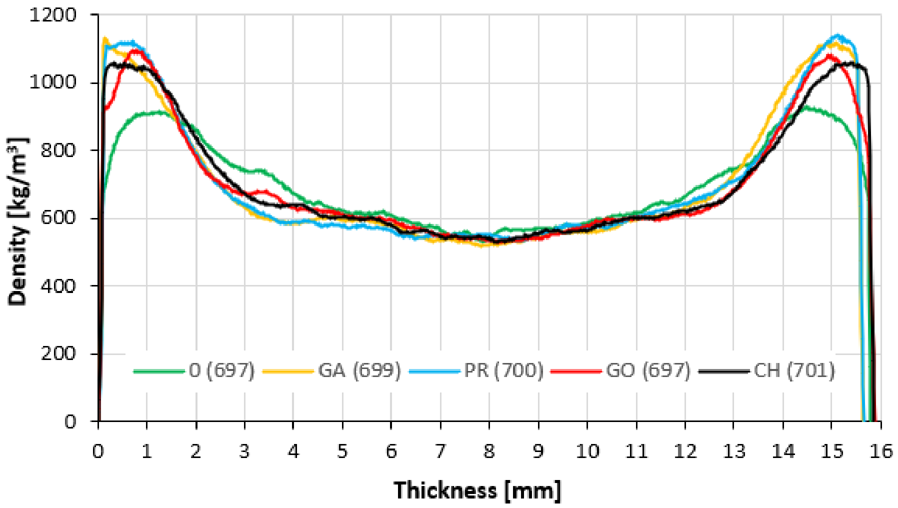

Figure 9. Density profiles of the particleboards made of different species of apple tree (average density in parenthesis)

SUMMARY

- There are differences in wood density between GA, PR, GO and CH cultivars. This translates into the bulk density of the core and face layer particles for individual species.
- Despite similar water absorption, after 2 hours and 24 hours for apple tree wood boards, there are differences in swelling depending on the thickness of the boards. Particularly high thickness swelling results can be seen for GA and GO samples.
- Internal bond is different for each apple cultivar panels. The GA cultivar is characterized by the highest durability, and the CH cultivar is characterized by the lowest durability. Only the CH sample does not meet the minimum internal bond strength required for P2-type according to the EN 312 standard.
- Modulus of elasticity and modulus of rupture confirm the compliance of the results for apple tree wood boards. Interestingly, all the boards met the requirements for the modulus of elasticity according to the EN 312 standard. None of them met the requirements for the bending strength according to the mentioned standard.
- The results of the screw withdrawal resistance, were particularly proper for the PR, GO and CH varieties, compared to the reference boards (0). For GO and CH samples, the resistance was even higher than for reference samples.
- Studies such as water absorption, internal bond, modulus of elasticity, screw withdrawal resistance and density profile confirm, that some apple cultivars wood can be an important and key addition in the mass production of particleboards.

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Streszczenie: *Wybrane właściwości płyt wiórowych wykonanych z cząstek drewna różnych kultywarów jabłoni*. Celem badań było określenie gęstości drewna oraz możliwości wykorzystania wiórów z różnych gatunków drewna jabłoni do produkcji płyt wiórowych. W badaniach wykorzystano następujące kultywary jabłoni: Gala (*Malus domestica* Borkh), Prince (Red Jonathan Cltv.), Golden Delicious (*Malus domestica* 'Golden Delicious' Cltv.), Champion (*Malus domestica* 'Szampion' Cltv.). W ramach pracy wyprodukowano w warunkach laboratoryjnych trójwarstwowe płyty wiórowe z wiórów powstałych z gałęzi oraz zbadano wybrane właściwości fizyczne i mechaniczne uzyskanych płyt, jak również gęstości drewna samych gałęzi. Badania potwierdziły występowanie różnic między gęstością badanego drewna jabłoni, jak również między właściwościami wytworzonych płyt wiórowych. Badania wykazały również możliwości produkcji płyt dla przemysłu meblarskiego z wykorzystaniem drewna wspomnianych kultywarów jabłoni.

Słowa kluczowe: płyta wiórowa, surowiec alternatywny, jabłoń, właściwości mechaniczne, właściwości fizyczne

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