Particleboard Surface Optimization for High-Quality Laminating with Decor Paper

Coskun Kursun,[a] Saadettin Murat Onat,[a,*] Orhan Kelleci,[b] and Suheyla Esin Koksal,[b]

* Corresponding author: orhankelleci@ibu.edu.tr

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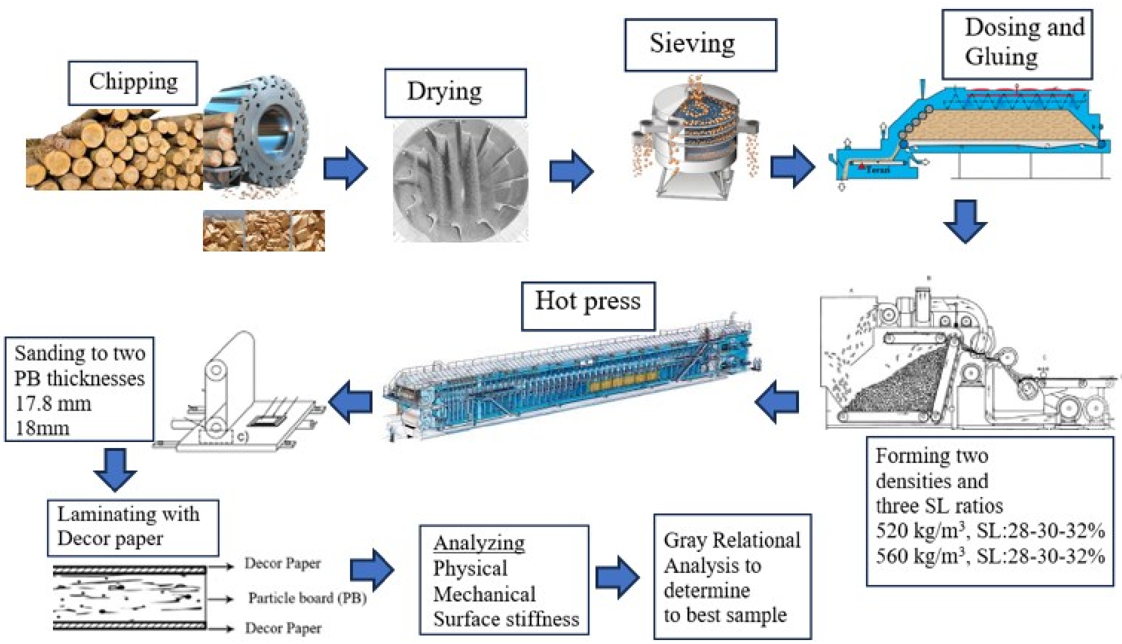
GRAPHICAL ABSTRACT



Particleboard Surface Optimization for High-Quality Laminating with Decor Paper

Coskun Kursun,[a] Saadettin Murat Onat,[a,*] Orhan Kelleci,[b] and Suheyla Esin Koksal,[b]

The level of wood consumption is important in particleboard (PB) manufacturing because wood is a natural source. This study aimed to determine the optimum wood consumption in PB manufacture. The study examined how the PB's surface (SL) and core (CL) layer ratio and sanding tolerance affect the PB surface laminating condition. The optimal manufacturing conditions were determined among different combinations of PB density (520 or 560 kg/m^3), SL/CL ratio, and sanding thickness using the multi-criteria decision-making method (MCDM). Grey relational analysis (GRA) was used as MCDM. Samples were characterized according to TS EN 312. The moisture content (MC) increased (30%) as the SL ratio increased. Thickness swelling (TS) and water absorption (WA) generally decreased as SL increased. Increasing surface layer density and board density significantly improved internal bond (IB) strength and surface stiffness (SS). Modulus of rupture (MOR) and elasticity (MOE) decreased as the sanding tolerance increased. Surface and edge screw withdrawal (SRy and SRk) resistance were increased as the density, sanding tolerance, and surface density increased. This study is the first comprehensive optimization approach to improve quality in coating low-density particle boards with decorative paper, potentially leading to material savings and production efficiency for the furniture and coating industries.

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Keywords: Thickness; Density; Laminate; Decor paper; Particle board; Sanding

*Contact information: a: Department of Forest Industry Engineering, Bartin University, Box 74100, Bartin, Türkiye; b: Department of Forestry, Mudurnu Sureyya Astarci Vocational School, Bolu Abant Izzet Baysal University, Box 14100, Bolu, Türkiye; *Corresponding author: orhankelleci@ibu.edu.tr*

INTRODUCTION

The rapid increase in the human population has resulted in a corresponding rise in wood consumption (Kauppi *et al.* 2018; Ke *et al.* 2019). Therefore, innovative forest products have been developed to reduce massive wood consumption. Among these products, particleboard (PB) is one of the most significant (Thoroe *et al.* 2004; Kirilenko and Sedjo 2007; Kauppi *et al.* 2018). The PB is shaped under temperature and pressure by gluing chips produced from wood and lignified lignocellulosic materials using various synthetic adhesives (Özen and Kalaycıoğlu 1980; Vick 1999; TS EN 309 2008; Frihart 2015; Maraveas 2020; Mirski *et al.* 2020). The production of PB is increasing annually. The global PB production has exceeded 100 million m^3 (Oliveira *et al.* 2016; Niemz and Sandberg 2022). PB is environmentally friendly because it can be produced from waste wood or wood parts left over from logging production (Zhang and Hu 2014; Owodunni *et al.* 2020; Reh *et al.* 2022).

Particleboard plays a crucial role in furniture production due to several advantages, including fewer defects compared to solid wood, the ability to be manufactured in desired sizes, ease of processing, rapid production speed, and high efficiency (Nemli *et al.* 2005; Zhang and Hu 2014; Pang *et al.* 2018; Astari *et al.* 2019; Mohd *et al*. 2019; Solt *et al.* 2019; Pędzik *et al.* 2021). Consequently, the use of PB in furniture manufacturing has increased significantly. However, PB producers face challenges in sourcing wood waste and leftover materials from logging operations. In response, manufacturers are focusing on the production of low-density PB to minimize reliance on raw wood materials (Zhao *et al.* 1995; Shalbafan *et al.* 2013; Benthien *et al.* 2019; Bednarczyk and Boruszewski 2022; Boruszewski *et al.* 2022). This shift aims to create more economical board products while addressing sustainability concerns.

Sustainability in particleboard production is becoming increasingly important in protecting forest resources and reducing environmental impacts. The use of agricultural biomass and recycled wood waste, in particular, reduces raw material costs and contributes to circular economy principles (Lee *et al*. 2022). Closed-loop production systems increase resource efficiency and reduce greenhouse gas emissions by encouraging waste reuse (Camilleri 2018). With its long-lasting product design and energy-efficient production techniques, this approach is increasingly preferred in the furniture and construction sectors (Hysa *et al.* 2020).

However, using low-density particleboard (PB) presents certain challenges, such as the adhesive curing into the impregnated decor paper during the laminate press processing. High pressure is typically applied to laminate the surface of PB with decor paper (Iwashitam and Stashevskr 1964; Nemli and Çolakoğlu 2005). It is important to note that this pressure should not exceed the pressure used during PB production; otherwise, the thickness of the PB may be reduced, resulting in substandard production quality (Flores *et al.* 2011; Gonçalves *et al.* 2020).

To address these issues, PB manufacturers have attempted to adjust the pressing conditions for laminating low-density PB with decor paper (Nemli and Çolakoglu 2005). However, these adjustments have proven ineffective, as the temperature, pressure, and press time must meet specific requirements for the resin in the decor paper to cure properly and adhere to the PB surface, allowing for minimal tolerance for variation (Istek and Ozlusoylu 2021). Consequently, optimizing the PB density, sanded end thickness, and SL ratio is necessary to achieve the most suitable form of PB.

Options for improving the surface quality of PB are limited. Increasing the SL ratio is one practical approach to achieving greater surface smoothness (İstek *et al.* 2017). In this case, more wood material is used because the SL layer is denser than the core layer (CL) (İstek *et al.* 2018). Additionally, more glue was used in the SL layer than in the CL layer (Kelleci 2013). This situation causes glue costs to increase, and the board's formaldehyde emissions are high (İstek *et al.* 2018; Kristak *et al.* 2023). The optimal SL ratio required for the smoothest board surface must be determined in this case.

Before laminating the board with decor paper, the surface thickness calibration must be performed by sanding (Chapman 2006; Nemli *et al.* 2007). The sanding tolerance should be as low as possible because excessive sanding tolerance removes the hard and dense SLs. However, a hard and dense surface is desirable during the lamination stage (Thoemen *et al.* 2010). Therefore, to obtain the best surface quality, the optimum sanding tolerances of boards must be determined.

The results obtained from this analysis must be carefully evaluated to determine the optimum PB sample. Various methods have been used to determine the optimal properties.

Many researchers have recently begun using multi-criteria decision-making methods (Srdjevic 2005). These advanced methods provide a precise framework for determining the optimal decision (Behzadian *et al.* 2010; Govindan *et al.* 2013). Verbal statements are inherently less precise than numerical data. The concept of a verbal variable is a tool for characterizing phenomena that are too complex or poorly defined for traditional quantitative analysis (Herrera and Herrera-Viedma 2000). Ensuring the relationship between verbal explanations and mathematical precision is challenging and vital.

The most important mechanical properties in the PB industry that determine board quality are the modulus of rupture (MOR) and internal bond (IB). High values in these quantities often are associated with high values of other mechanical properties. It is generally accepted in the PB industry that PB with high mechanical properties will also have good physical properties such as thickness swelling (TS) and water absorption (WA). In the Gra method, the quality characteristic of the type "larger is better" is utilized to enhance the performance of the mechanical properties of particleboards. Consequently, the "bigger is better" criterion was selected for the parameter optimization. The GRAY method was applied to PB with superior properties (Taguchi and Cariapa 1993; Kasemsiri *et al.* 2017; Sumesh and Kanthavel 2022). For instance, Kelleci *et al.* (2022a) employed Grey relational analysis to optimize the fabrication parameters to improve the mechanical properties of biopolymer (polylactic acid and polyhydroxybutyrate) wood dust blends. Kasemsiri *et al.* (2017) utilized the Taguchi method in conjunction with Grey relational analysis to optimize biodegradable foam composites. Similarly, Sumesh *et al.* (2022) conducted a study on optimizing various parameters that affect the mechanical properties of banana/coir natural fiber composites using Grey relational analysis and artificial neural networks.

Producing the highest quality board with minimal wood use is crucial in the PB industry. Wood accounts for approximately half of production costs. Furthermore, being biomaterial sourced from forests creates supply problems. Therefore, numerous studies in literature have focused on production with low wood use or alternative lignocellulosic materials (Weigl *et al.*; Kawai and Sasaki 1986, 1993; Rowell *et al.* 1995; Shalbafan *et al.* 2016; Boruszewski *et al*. 2022). However, these studies have not simultaneously investigated the effects of density, surface layer amount (or density), and sanding tolerance during thickness calibration on board quality. The presented study results provide data from which the existing industry will benefit.

This study aimed to improve lamination quality by determining the optimal SL ratio and sanding tolerance in low-density particleboards. This study presents an innovative approach to optimizing production parameters by GRA Analysis. This method is of industrial importance because it aims to determine the optimum SL, CL ratio and sanding tolerance for PB manufacturing. Production costs can be reduced, and board surface quality can be improved, contributing to sustainable and high-performance PB development by using less wood consumption in SL and CL.

EXPERIMENTAL

Materials

Wood was purchased from a local market. Black pine (50%), poplar (20%), fir (10%), and industrial waste wood sawdust (20%) were used after primary chipping. All woods were residual wood from the production of timber and other forest products from the forest. The woods were chipped into dimensions between 0.2 to 4 mm using a HAKER brand drum chipper. Then, wood chips were milled by a 0.65-mm knife distance in the second chipper. After the chips were dried, they were sieved, and those between 0.2 and 1 mm were used for the SL layer, and those between 1 and 4 mm were used for the CL layer. SL and CL wood particles were dried at approximately 1 to 1.5%

Urea formaldehyde (UF) glue and ammonium sulfate (AS) hardener were supplied by Yıldız Entegre. UF was used to glue the chips at a solid concentration of 65%. AS, at a concentration of 33% was used as the hardener. The properties of the UF resin and AS hardener for the SL and CL layers are listed in Table 1.

Table 1. Some Properties of UF and AS

Parameters	SL	CL
UF Density (g/cm^3)	1.184	1.284
UF pH (0-14)	7.3	7.4
UF Viscosity (cp)	300	310
UF temperature (°C)	21	22
Hardener (AS)/UF (%)	3.5	1.1
UF gel time (s)	77	44

Preparation of Samples

PBs were produced industrially in 18 mm x 2100 mm x 2800 mm dimensions at the Yıldız Entegre company in Bolu, Turkey. Wood at 65% moisture was primarily chipped in a HAKER drum chipper with a 3 mm knife distance (Fig. 1a). It was secondarily chipped using MAIER ring mills at a knife distance of 0.65 mm (Fig.1b). It was then dried in a Bütner drum dryer to 1.5% moisture (Fig. 1c).

The dried wood chips were glued to the SL and CL layers using special glue recipes (Fig. 1d). The glue recipes prepared for SL and CL are presented in Table 1. Wood chips at 1.5% moisture were blended with UF and AS in a blender, according to the proportions listed in Table 2. After gluing, the SL and CL humidities were 15% and 7%, respectively. SL chips were used at three different rates (28-30-32%).

A board draft (mat) was formed to be corrected as the glue blended material was formed into a mat (Fig. 1e). Initially, the thickness of the mat formed was approximately 54 mm. Mat was pressed at 5 kg/cm^2 in a pre (cold) press machine. The mat thickness was reduced to 30 mm using a prepress.

During hot pressing, the board was pressed at 190 °C and under 38 kg/cm^2 pressure for 85 s using a Seimpelkamp control press (Fig. 1f). The pressing factor was 5 s/mm for board sample production. The board thickness was 18.3 to 18.4 mm, and the temperature was approximately 100 °C at the end of the hot press. The boards were produced at two densities (520 and 560 kg/m^3).

The boards were conditioned (Fig. 1g) at room temperature for two days. The boards were cooled to 22 °C, and the thickness was calibrated using a Steinemann Sanding Machine (Fig. 1h). The 100-120-180 grid polishing paper was used to sand the PB surfaces. PBs were sanded to two different thicknesses (17.8 mm and 18.0 mm). Twelve different sample groups were prepared with two densities, three SL ratios, and two sanding thicknesses. Eight replicate tests were performed for each sample in each group.

PBs surfaces were laminated with 252 g/m^2 white decorative paper impregnated with melamine (20%) and urea formaldehyde (80%) resin at 185 °C and under 35 kg/cm^2 pressure for 30 s (Fig. 1i). The laminate process was performed on a 500 mm x 500 mm

PB sample in a laboratory type press. Equal laminate conditions were used for all the sample groups, as shown in Table 2.

Table 2. Prepared Samples Properties

Samples	Density (kg/m^3)	Sanded Board Thickness (mm)	SL (Bottom) (%)	SL (Top) (%)	CL (%)	UF/Wood SL (%)	UF/Wood CL (%)	AS/UF in CL (%)	AS/UF in SL (%)
P1	520	17.8	14	14	72	14	7.5	3.5	1.1
P2	520	18	14	14	72	14	7.5	3.5	1.1
P3	520	17.8	15	15	70	14	7.5	3.5	1.1
P4	520	18	15	15	70	14	7.5	3.5	1.1
P5	520	17.8	16	16	68	14	7.5	3.5	1.1
P6	520	18	16	16	68	14	7.5	3.5	1.1
P7	560	17.8	14	14	72	14	7.5	3.5	1.1
P8	560	18	14	14	72	14	7.5	3.5	1.1
P9	560	17.8	15	15	70	14	7.5	3.5	1.1
P10	560	18	15	15	70	14	7.5	3.5	1.1
P11	560	17.8	16	16	68	14	7.5	3.5	1.1
P12	560	18	16	16	68	14	7.5	3.5	1.1

Fig. 1. Samples prepared at a real manufacturing line in Bolu province/Turkey; a) primer chipper, b) seconder chipper, c) drying, d) gluing, e) forming, f) pressing, g) climatizing, h) sanding, and i) laminating station.

Methods

Surface tests (such as abrasion, scratch, and stain resistance) were not conducted on uncoated PB. Because surface tests are performed on coated PBs according to the TS EN standard. Also, PB is typically used in furniture production after being coated. Coated PB (suitable for furniture use) is subjected to abrasion, scratch, and stain resistance tests. Therefore, according to the TS EN standard, physical and mechanical tests were conducted on uncoated boards, and surface tests were conducted on coated boards. Physical characterization of the samples was performed using moisture content (MC), thickness swelling (TS), water absorption (WA), density (DN), and color (CO) analyses according to TS EN 322 (1999), TS EN 317 (1999), TS EN 323 (1999), and TS EN 438-2 (2019) respectively. Mechanical characterization of the samples was carried out using modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB), surface stiffness (SS), and screw withdrawal resistance (SR) analyses according to TS EN 310 (1999), TS EN 319 (1999), TS EN 311 (2005), and TS EN 320 (2011), respectively. All of the listed TS EN standards are the latest and most up-to-date standards. The surface durability of the laminated samples was characterized by abrasion (AR), scratch (SC), and stain (water, soap, tea, coffee, acetone, acid, and cigarette fire) resistance (ST) analyses, according to TS EN 13329 +A2 (2021), TS EN 15186 (2012), and TS EN 14323 (2006), respectively (Fig. 2). The edge density profiles of the samples were determined using a GreCon DA-X X-ray device. Four 50 × 50 mm samples taken from laminated particleboards were measured, and the analysis yielded the top and bottom layer maximum densities, minimum density points, distance between peak densities, and center density ratios. The results were analyzed using SPSS software. The variance analysis and the Duncan test revealed differences within and between groups.

Fig. 2. Particleboard laminating and characterization

The GRA method was applied to determine the optimum SL ratio, density, and sanding tolerance in PB for the best surface quality of laminated PB. The entropy-based

GRA method was used to select the best sample among the analysis samples. The entropy method was used to weigh these criteria. The entropy method was used to determine the weight of several different criteria. In this method, the entropy value was used to determine the importance of each criterion. This method enables the objective determination of weight by considering the relationships and interactions between different criteria. It is an effective method for determining weights in complex and multidimensional datasets, and consists of the following stages (Wang and Lee 2009).

Stage 1: In the entropy method, the decision obtained was the first set of criteria. i. (Eq. 1)

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccccc} X_1 & X_2 & \dots & X_j & \dots & X_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1j} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2j} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \dots & x_{ij} & \dots & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mj} & \dots & x_{mn} \end{bmatrix} \end{array} \quad (1)$$

Here, x_{ij} refers to the j^{th} alternative value reached according to i^{th} criteria. $i = 1,2,\dots,m$ and $j = 1,2,\dots,n$.

Stage 2: Normalization of the decision matrix is calculated using Eq. 2,

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad , i = 1,2,\dots,m \, , j = 1,2,\dots,n. \quad (2)$$

where I is the alternatives, j is the criteria, p_{ij} is the normalized values, and x_{ij} is the given benefit value.

Stage 3: The Entropy value for each criterion is calculated using Eq. 3,

$$e_j = -k \sum_{i=1}^{m} r_{ij} \ln r_{ij} \, , \qquad j = 1,2,\dots,n \ . \quad (3)$$

where k is the $(\ln(n))^{-1}$, k is the entropy coefficient, e_j is the entropy value, p_{ij} is the normalized value.

Stage 4: The weight value of each criterion was calculated using Eq. 4,

$$w_j = \frac{1 - e_j}{\sum_{p=1}^{n}(1 - e_p)} \qquad , \quad j = 1,2,\dots,n \ . \quad (4)$$

where w_j is the weighted value, and e_j is the entropy value. With Eq. (4), the criterion weights are calculated. Here, the sum of the weights was equal to one. In other words, $\sum_{j=1}^{n} w_j = 1$.

The Grey relational analysis method is commonly used to optimize multiple performance characteristics. The steps used in this method (Pawade and Joshi 2011; Khan *et al.* 2012; Panda *et al.* 2016) are given below.

Design and Implementation of the Experiment

The n-dimensional series consisting of the obtained data (x_0) is expressed by Eq. 5.

$$x_0 = \left(x_0(1), x_0(2), x_0(3), \ldots, x_0(n)\right) \tag{5}$$

Normalization of data and weighting of normalized data

During normalization, an equation suitable for the needs of the problem is used. These equations are better, smaller, and nominally better. If it is more appropriate for the criterion value to be larger after normalization, Eq. 6 is used:

$$x_i(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{6}$$

If it is more appropriate for the criterion value to be small after normalization, Eq. 7 is used,

$$x_i(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{7}$$

where i = 1,..., m; k = 1,..., n; m is the number of experimental data points, and n is the number of responses. $x_i^0(k)$ denotes the original array, $x_i^0(k)$ denotes the sequence after data preprocessing, max $x_i^0(k)$ denotes the largest value of $xi^0(k)$, min $x_i^0(k)$ denotes the smallest value of $xi^0(k)$, and x is the desired value.

The normalized decision matrix was created using Eq. 8:

$$x_i = \left(x_i(j)\right) \quad i = 1,2, \ldots m; \quad j = 1,2, \ldots n \tag{8}$$

The ranking scores of the factors and options were calculated using Eq. 9:

$$\xi_i(k) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{0i}(k) + \xi\Delta_{max}} \tag{9}$$

Here, located in the range [0.1], it is defined as the discriminating coefficient or contrast control coefficientξ. $\xi = 0.5$ It is widely used. Δ_{min} and Δ_{max} are the minimum and maximum values (Eq. 10) of the absolute differences (Δ_{0i}) of all comparison sequences.

$$\begin{aligned} \Delta_{0i}(k) &= |x_0(k) - x_j(k)| \\ \Delta_{min} &= \min_i \min_j \Delta_{0i}(k) \\ \Delta_{max} &= \max_i \max_j \Delta_{0i}(k) \end{aligned} \tag{10}$$

The Grey relational degree was then calculated. If the importance of the criteria in the decision matrix is equal, the grey relational degree (Γ_{0i}) is determined using Eq. 11:

$$\Gamma_{0i} = \frac{1}{n}\sum_{k=1}^{n} w_j \xi_i(k) \tag{11}$$

RESULTS AND DISCUSSION

Physical Properties

The physical analysis results are given in Table 3. The MC of the samples increased as the SL ratio increased (Fig. 3a). This increase was expected because of the use of a more aqueous UF solution for gluing the SL. During the sanding process, the MC of the boards sanded to 17.8 mm was higher than those sanded to 18 mm. This situation was not the same, for example, where 16% SL was used. When the boards were sanded to 17.8 mm, the moist and dense SL layer was removed from the surface. In this case, the surface density and MC of the boards were expected to decrease. However, it was determined that the MC of the boards (P1, P3, and P7) sanded to 17.8 mm was higher than those sanded to 18 mm (P2, P4, and P8). The dense SL layer on the board surface can prevent moisture exchange with the external environment. Thinning the dense SL layer after sanding can allow moisture to be absorbed from the external environment. This may increase the MC.

The MC is an important parameter during PB production and at end-use sites. Aydin (2016) examined the effect of MC on the physical and mechanical properties of PB mats and reported that the optimum MC should be between 14% for SL and 6 to 7% for CL. In the current study, the same results were obtained (MC of SL: 14% and CL: 6.5%).

Table 3. Physical Analysis Results of Unlaminated Samples

Samples	MC (%)	TS2h (%)	TS24h (%)	WA2h (%)	WA24h (%)	Density (kg/m^3)
P1	5.4 B* (± 0.07)**	10.3 G (± 0.6)	17.2 C (± 1)	56.3 G (± 5.8)	96 E (± 4.7)	515 A (± 18)
P2	5.1 A (± 0.02)	7.0 E (± 1)	16.4 B (± 0.7)	48.6 F (± 2.3)	87 CD (± 2.5)	523 A (± 3.3)
P3	6.5 G (± 0.03)	4.7 CD (± 1)	15.8 B (± 1.1)	36.7 B (± 5.6)	82 ABC (± 6)	515 A (± 12)
P4	6.0 D (± 0.1)	3.6 AB (± 0.8)	15.8 B (± 0.7)	33.4 AB (± 4.5)	81 ABC (± 8.7)	525 A (± 17)
P5	6.4 F (± 0.1)	4.0 BC (± 0.9)	15 A (± 0.9)	40.9 C (± 5.4)	87 CD (± 4.7)	513 A (± 10)
P6	6.9 I (± 0.1)	3.1 A (± 0.08)	15.7 B (± 0.3)	42.4 CD (± 0.7)	86 BCD (± 7.1)	523 A (± 12)
P7	6.1 E (± 0.06)	7.4 EF (± 0.7)	18.6 D (± 0.2)	46.3 EF (± 5.3)	89 D (± 5)	553 B (± 7.7)
P8	5.8 C (± 0.08)	7.8 F (± 1)	19 D (± 0.9)	47.1 F (± 5.5)	90 D (± 4)	562 B (± 12)
P9	6.0 D (± 0.07)	4.0 BC (± 0.4)	16.4 B (± 0.2)	31.8 A (± 3.9)	77 A (± 4.6)	558 B (± 13)
P10	6.7 H (± 0.1)	5.3 D (± 0.6)	17.2 C (± 0.1)	34.8 AB (± 3.7)	81 AB (± 5)	547 B (± 8.8)
P11	6.7 H (± 0.1)	5.4 D (± 0.4)	17.3 C (± 0.4)	35.3 AB (± 1.1)	79 A (± 1.1)	561 B (± 6.6)
P12	6.7 H (± 0.1)	5.4 D (± 0.5)	17.3 C (± 0.4)	35.3 AB (± 3.2)	79 A (± 1.1)	561 B (± 5.9)

*Standard deviation, ***Post-hoc* DUNCAN test

As SL increased, TS generally decreased. This may be caused by the increase in wood content and the resulting increase in density and increase in glue in the content. Thus, as SL increased, TS decreased (Fig. 3b). The 17.8 mm sanded board swelled more than the

18 mm board. This is believed to be because the SL layer is denser and contains more glue. Sanding the SL layer (From 18 mm to 17.8 mm), which is denser and contains more UF than the CL layer, increased the TS.

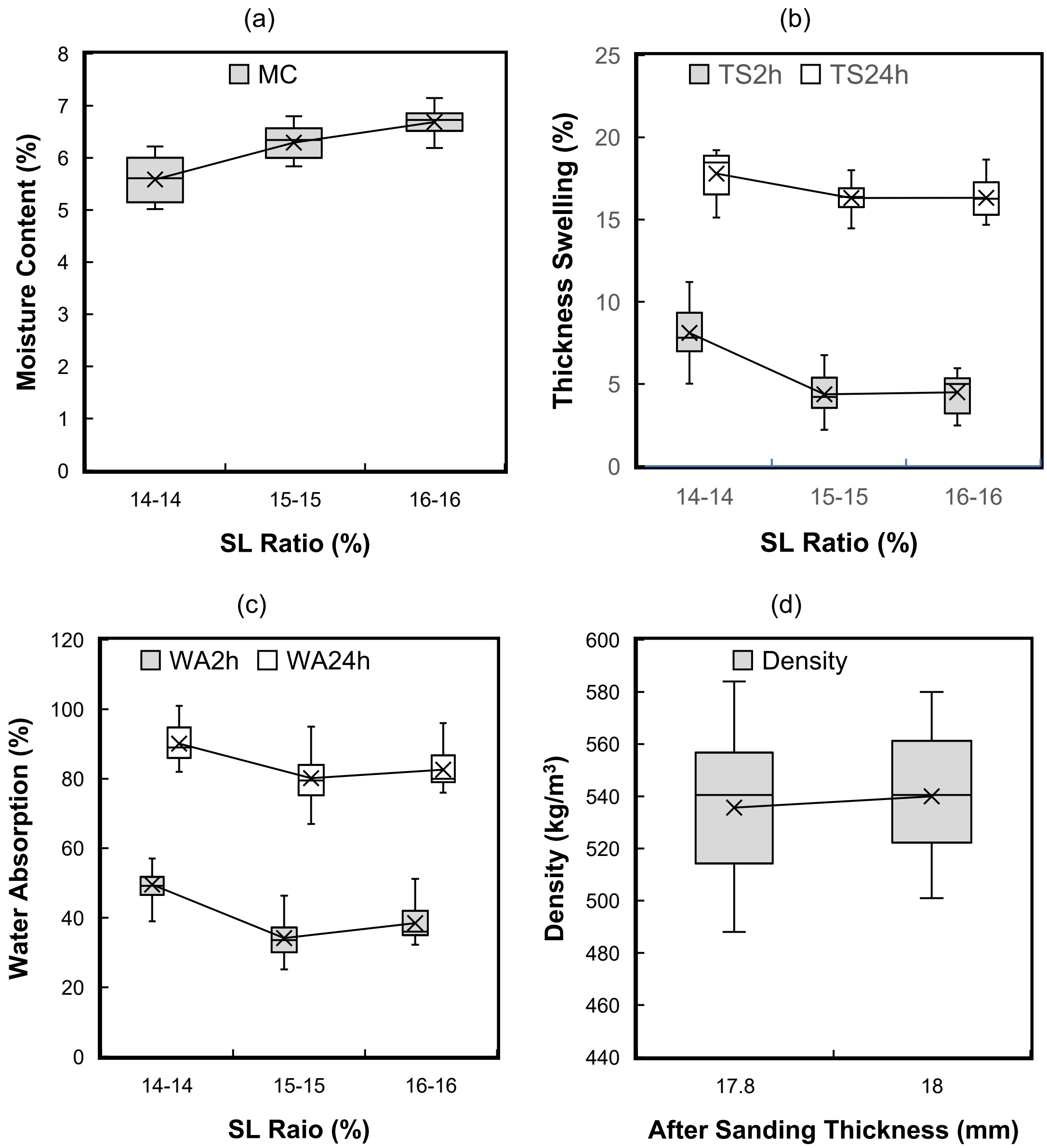

Fig. 3. Physical properties of unlaminated PBs: (a) MC, (b) 2-h and 24-h TS, (c) 2-h, and 24-h WA, and (d) Density of unlaminated samples

Analysis revealed that the minimum density of the samples with an average density of 520 kg/m³ was 490 kg/m³ (Table 4), measured at the mid-thickness of the board, whereas the samples with an average density of 560 kg/m³ exhibited a lower minimum density of 480 kg/m³ (Table 4) in the same region. This discrepancy may explain the comparatively weaker water resistance of the 560 kg/m³ samples relative to those with a 520 kg/m³ density. Furthermore, the peak-to-peak density variation (mm) across the samples appears to influence the relationship between density and water resistance. The 520 kg/m³ samples demonstrated an average peak-to-peak distance of 15.2 mm, while the 560 kg/m³ samples showed a slightly larger variation of 15.7 mm. This increased heterogeneity in density distribution may have contributed to accelerated water absorption from the middle layer in the higher-density samples. When the WA of the boards produced at a density of 520 kg/m^3 was examined, an increase in WA was determined in P1 to P2 samples. No significant change was detected in the P3 to P6 samples. In this case, it can be concluded that a decrease in the SL ratio affects the WA of the samples. As the SL ratio increased, the WA decreased (Fig. 3c).

When the WA of samples with a 560 kg/m3 density was examined, no significant difference was detected between the WA in the P8 to P12 samples. The thickness of the sanded board (from 18 mm to 17.8 mm) did not significantly affect their WA. In this case, it can be concluded that a decrease in the amount of SL caused the PBs to absorb more water. In addition, the thickness after sanding did not cause significant differences in the WA of the P7 to P12 samples.

It was determined that the change in SL amount (from 14% to 16%) and the sample thicknesses after sanding (17.8 mm and 18 mm) did not cause a significant difference in the density of the samples. When P1 to P6 were examined (Fig. 3d), when the board thickness decreased after sanding, the board density decreased. The board density increased as the board thickness increased, except for the P8 to P9 sample, when the density distributions of the P7 to P12 samples according to their thickness after sanding (Fig. 3d) were examined.

The quality of the SL in a particleboard is one of the most important factors affecting board quality (Istek and Ozlusoylu 2021; Kelleci *et al.* 2022b). The decrease in the surface density of the board prevents the decor paper from strongly adhering to the board surface. This causes the problem called cracking at the edges during the cutting process of a board with a circular saw (Köksal and Kelleci 2020). Nemli *et al.* (2005) determined that the PB surface smoothness increased with the press pressure, amount of chips on the surface, and density. They also reported that using beech chips on the surface created a smoother surface than pine chips.

Density profile analysis was applied to the laminated PB samples; the results are presented in Table 4. According to the results, the laminate press affected the top and bottom surface densities. The bottom surface was 28% denser than the top surface. The surface-layer densities of P7 to P12 were 1 to 2% higher than P1 to P6. However, the differences were not statistically significant.

In particleboard manufacturing, it is desirable that the surface density is high and that the CL density is low. In this case, increasing the board density increases the quality but causes an increase in cost. In this case, it is necessary to determine the optimum amount of the CL and SL. It is desirable that the board surface density be over 1000 kg/m^3 on the sanded board surface. Determining the amount of SL, sanding tolerance, and board density that will ensure this is extremely important for reducing board manufacturing costs. The CL density of the board can be reduced as much as possible, provided that the edge screw withdrawal resistance (SRk) remains within the standards (Wong *et al.* 1999).

Reducing the middle-layer density also significantly affects the physical properties of the board. The amounts of WA and TS increased as the CL density decreased, which is undesirable. As SL increases, CL densities decrease because the pressing pressure is transmitted from SL to CL. Thicker SL reduces the pressure transmission to CL. Lower density CL absorbs more water and swells (Istek *et al.* 2017, 2019). To prevent this situation, paraffin (1 to 3%) was used in the glue in the board's middle layer (Nemli *et al.* 2011; Baharoğlu *et al.* 2014).

Table 4. Density Profile Results of Laminated PB Samples

Samples	*1Max. Left Den. (kg/m³)	*2Min. Den. (kg/m³)	*3Max. Right Den. (kg/m³)	*4Peak-peak Den. (mm)	*5Avarage den. (kg/m³)	*6Cen. Den. /Avg. Den. (kg/m³)	*7Min. Den. Pos. (mm)	*8Centr. den. (kg/m³)	*9Min. den. /centr. (%)
P1	1373	490	1200	15.40	627	79	7.8	497	78
P2	1428	565	1086	15.50	645	80	7.45	513	78
P3	1417	499	1273	15.40	644	80	8.20	512	77
P4	1371	462	1106	14.75	602	79	7.7	473	77
P5	1409	487	1015	14.85	627	79	7.4	495	78
P6	1391	492	1104	15.30	627	81	9.1	510	78
P7	1445	498	1175	16.0	649	78	7.3	506	77
P8	1398	496	1069	16.25	629	82	5.6	517	79
P9	1432	485	1088	15.40	626	79	7.6	492	77
P10	1435	498	1106	15.95	645	79	8.35	506	77
P11	1401	484	1113	15.05	639	77	8.15	492	76
P12	1395	480	1154	15.65	634	77	7.45	489	76

*1: Maximum Left density (kg/m³), *2: Minimum density (kg/m³), *3: Maximum right density (kg/m³), *4: Peak-Peak density (mm), *5: Average density (kg/m³), *6: Center density /Average Density (%), *7: Minimum density point (mm), *8: Center Density (kg/m³), *9: Minimum density/Central Density (%)

Mechanical Properties

The mechanical analysis results for the sanded PBs are listed in Table 5. When the density increased from 520 to 560 kg/m³, the MOR strength increased 32% (Fig. 4a). As MOR increased, MOE increased at the same rate (Fig. 4b). No significant difference was detected in the MOR strengths of the samples as the amount of SL increased.

The thickness differences after sanding significantly affect the MOR strength. The 0.2 mm thickness tolerance caused an approximately 16% difference in the MOR strength of the board. Because the thickness of the wood chips used in the SL is between 0.2 and 1 mm, they contain more glue (UF) than CL chips with a thickness of 1 to 4 mm. As the wood chips became smaller, their surface area increased. Increasing the surface area causes more glue to adhere to the surface, making the boards denser (Lee *et al.* 2022).

It is important to determine how many millimeters from the surface will be sanded during the thickness calibration with sandpaper (Köksal and Kelleci 2020; İstek *et al.* 2020). Because the SL is the visible part of the board, visual defects can be easily observed. Defects, such as low board surface density, sanding errors, and the presence of tree bark on the surface, cause quality problems on the board surface during the melamine-pressing stage (İstek *et al.* 2017). In this study, going too deep (from 18 to 17.8 mm) from the board surface during the sanding process caused the hard and dense SL layer to be stripped away. This caused the MOR and MOE strengths to decrease in the board. The PB emerging from the press must be sanded for thickness calibration. The smaller the sanding tolerance (thickness tolerance), the better (Kurşun 2024). Therefore, the results demonstrate the impact of thickness tolerance on MOR and MOE.

The board thickness after sanding did not cause significant differences in the IB force. The IB strengths of samples (P1 to P6) with densities of 520 kg/m³ and (P7 to P12) 560 kg/m³, respectively, were not statistically significant. Although there was a density difference of 7.5% between the (P1 to P6 and P7 to P12) samples, it was determined that there was no difference in the IB strength (Fig. 3c). However, it was determined that density fluctuations were greater in samples (P1 to P6) with a density of 520 kg/m^3, and the standard deviation was therefore high. The IB strength is expected to increase with board density. However, in this study, no change was noted in the IB strength even though the board density increased (Fig. 4c). The change in SL content slightly (3 to 5%) affected the IB strength. Similarly, the board thickness after sanding is not expected to affect IB strength. This is related to the density of the CL layer and the adhesion properties of the adhesive used. Studies in literature on PB density and IB strength confirm this (Korai 2021; Fehrmann *et al.* 2022). The SL ratio will indirectly affect the density of the CL layer because, in the press, pressure is transmitted from the SL layer to the CL layer. The hardness or softness of the SL layer affects the pressure transmitted to the CL layer. Therefore, IB resistance can be affected.

When the density increased from 520 to 560 kg/m^3, a 38% increase in the SS strength was recorded (Fig. 4c). A similar increase was observed in the MOR strength. The change in SL ratio did not cause significant changes in the SS of the samples. A 1 to 2% decrease was recorded in the SS from P1 to P2 to P3 to P4, and a 1 to 2% increase in SS was recorded from P3 to P4 to P5 to P6.

Decreasing the board thickness by 0.2 mm after sanding caused a 1 to 2% decrease in the SS. With the sanding process, the dense top layer of the board became thinner and reduced the surface durability. To ensure high surface durability, the top layer of the board should not be thinned as much as possible. However, some surface defects were not eliminated using sandpaper. In this case, the sanding tolerance should be maintained as low as possible (0.1 mm to 0.3 mm). This study determined that if the sanding tolerance was 0.2 mm, there was no significant difference in the surface durability.

Table 5. Mechanical Analysis Result of Samples

Samples	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)	SS (N/mm^2)	SRy (N)	SRk (N)
P1	6.7 A (± 0.9)	1683 A (± 126)	0.29ABC (± 0.03)	0.68 AB (± 0.07)	662 AB (± 48)	238 A (± 82)
P2	7.8 BC (± 0.5)	1845 (± 97)	0.29ABC (± 0.01)	0.72 BC (± 0.04)	712 ABC (± 36)	434 CDE (± 30)
P3	6.8 A (± 1.0)	1605 A (± 161)	0.26 A (± 0.02)	0.66 AB (± 0.04)	662 AB (± 61)	428 CD (± 54)
P4	7.4 AB (± 1.0)	1712 AB (± 154)	0.27 AB (± 0.04)	0.67 AB (± 0.04)	712 ABC (± 49)	466 DEF (± 30)
P5	6.8 A (± 0.5)	1593 A (± 91)	0.26 A (± 0.02)	0.62 A (± 0.13)	675 AB (± 37)	447 CDE (± 53)
P6	7.5 AB (± 0.9)	1636 A (± 156)	0.31 C (± 0.04)	0.76 C (± 0.06)	638 A (± 65)	405 CD (± 54)
P7	9.6 CDE (± 1.0)	1908 C (± 169)	0.26 A (± 0.01)	0.98 E (± 0.07)	792 DE (± 81)	528 F (± 72)
P8	10.3 E (± 0.8)	1997 C (± 163)	0.28ABC (± 0.02)	0.99 E (± 0.07)	722 BC (± 79)	388 C (± 84)
P9	9 CD (± 0.7)	1864 BC (± 128)	0.28ABC (± 0.2)	0.93 DE (± 0.07)	729 BC (± 89)	299 B (± 73)
P10	9.2 CD (± 0.9)	1928 C (± 145)	0.26 A (± 0.1)	0.87 D (± 0.02)	760 CDE (± 114)	529 F (± 72)
P11	9 C (± 0.7)	1910 C (± 208)	0.30 BC (± 0.3)	0.96 E (± 0.09)	829 E (± 73)	497 EF (± 42)
P12	10 DE (± 0.8)	1997 C (±121)	0.29ABC (± 0.2)	0.96 E (± 0.09)	829 E (± 73)	497 EF (± 42)

*Standard deviation, ***Post-hoc* DUNCAN test

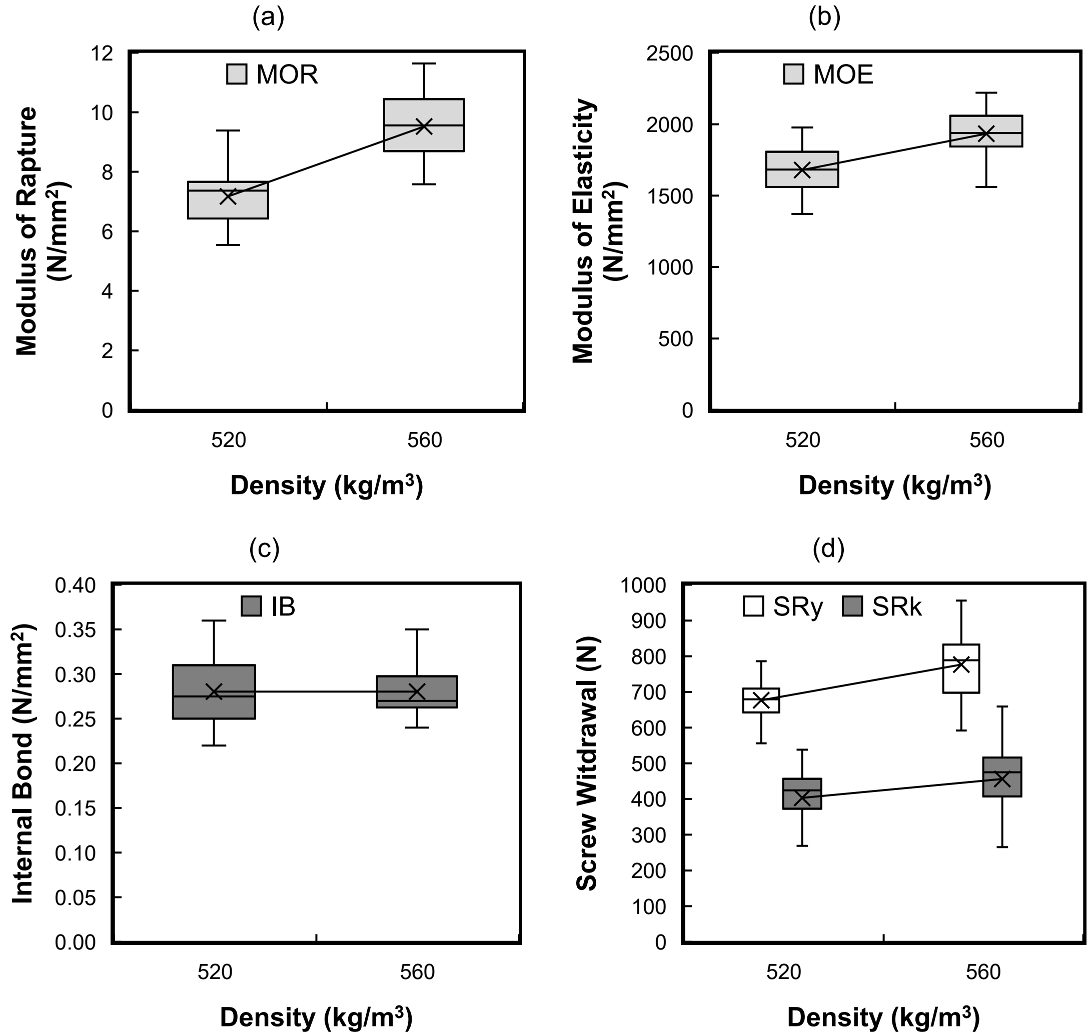

Fig. 4. Mechanical analysis graph: a) Modulus of rupture (MOR), b) modulus of elasticity (MOE), c) internal bond (IB), d) surface (SRy), and edge (SRk) screw withdrawal resistance rely on density

When the screw withdrawal resistance (SR) of the samples was examined according to density, an increase in density from 520 to 560 kg/m^3 caused a 15% increase in SRy resistance and a 13% increase in SRk resistance (Fig. 4d). It was expected that the SR resistance would increase with increasing density (Hu *et al.* 2023). Increasing the amount of wood and the amount of glue increased the SR. A 7.5% decrease in density caused an approximately 13 to 15% decrease in SR. When it is desired to reduce wood and glue consumption costs, this decrease can be ignored if it meets the TS EN 311 (2005) standard.

An increase in the SL amount increased the SR resistance. Although the SRy resistance decreased approximately 1% when the SL was increased from 14% to 15%, it increased approximately 4% when the SL was increased from 15% to 16%. SRk increased 8% from 14% SL to 15% SL and increased approximately 7% from 15% SL to 16% SL.

Overall, it can be concluded that increasing the SL content of the samples increased the SRy and SRk resistance. When the effect of board thickness on the SR resistance after sanding was examined, it was determined that the decrease in thickness caused a slight decrease (from 728 to 724 N). This result was expected, considering that the dense SL was removed by sanding.

Surfaces Mechanical Durability

The abrasion cycles of all the samples were between 200 and 240. The highest abrasion resistance was observed for P2, P4, P6, P8, P10, and P12. It is understood that reducing the board thickness (from 18 mm to 17.8 mm) with sanding causes the removal of the hard layer with a high density on the surface. This reduces the surface abrasion resistance of the board.

Variations in the board densities did not cause a significant change in the abrasion resistance. The surface-layer density and hardness of the board were more effective in terms of abrasion resistance than the total board density.

No significant difference was detected when the abrasion resistance was evaluated in terms of the SL content. The abrasion resistance decreased slightly from 14% to 15% but increased again to 16%. In this case, it was concluded that the thickness after sanding was more effective for surface abrasion resistance than the changes in the amount of SL.

The scratch resistance of all samples was the same. According to the TS EN 15186 (2012) standard, the surface scratch resistance of the particleboard must be 3 N and above. In this regard, it can be said that the scratch resistance of all the samples was within the standards. When the scratch resistance of the samples was evaluated in terms of density, the amount of SL and sanded board thickness was not significant. In this case, it can be said that the scratch resistance of the laminate surface depends on the quality of the decor paper on the surface, regardless of the sample density, SL amount, and sanded thickness.

Surface Stain Resistance

The samples were found to be quite resistant to acetone and coffee stains, and there were no visible changes on the board surface. There was a slight change in the brightness and color of the 520 kg/m^3 density boards (P1 to P6) with tea spilled on them. The exact change was not detected in samples (P7 to P12) that had a density of 560 kg/m^3. No effect of the amount of SL and thickness after sanding was detected on the resistance against tea, coffee, and acetone staining.

Water stain was detected only in samples with 560 kg/m^3 density and SL ratios of 15% and 16%, respectively. This was caused by changes in surface density. The denser sample surface was less abraded (Nemli *et al.* 2007). This did not cause a significant difference between the samples because there was a slight change in brightness and color when the samples were viewed.

The resistance levels to cigarette fire were the same in all the samples. There was a dark brown stain on the sample surface, but there was no deterioration in the surface structure. In a similar study, Muğla (2010) covered MDF surfaces with different coating materials and reported that the resistance of the tissue paper on the MDF surface to cigarette fire was Grade 2.

In the current study, the chipboard surfaces were laminated with white decor paper. However, the results were the same as those of the MDF board. In this case, it can be said that the type of board did not affect the resistance to cigarette fire. However, this situation needs to be subjected to further analysis. The changes in the SL ratio, density, and thickness after sanding were not significant in terms of resistance to cigarette fire. It was determined that samples with a density of 520 kg/m^3 were more resistant to pencil stains.

Istek and Ozlusoylu (2021) examined the effect of temperature and time changes on MDF properties in the lamination process and determined that the porosity was at level 3 under 205 °C and 18 to 20 s, and at level 4 under other conditions. The current study used the same temperature and pressure to produce all boards. There was no significant difference in the boards' SL amounts, densities, and post-sanding thickness after lamination. This situation can be explained as follows: no linear change was observed between 14 to 14%, 15 to 15% and 16 to 16% in 520 kg/m^3 density boards. The porosity first decreases and then increases. Changes in the amount of SL cannot explain this result. Similarly, the porosity was lower for the boards with a 560 kg/m^3 density.

The most significant difference between the samples was in the acid stain resistance. In the samples with a density of 520 kg/m^3, 3rd degree acid damage was detected on the surface of the samples, except for P3. It was determined that the samples with a density of 560 kg/m^3 were more durable. No significant difference was observed between the samples when acid resistance was examined in terms of SL ratio. When the acid-resistance levels of the samples were examined according to their thickness after sanding, it was determined that the 18-mm-thick samples were more resistant to acid damage. In this case, it can be said that the thickness after sanding is one of the most important factors affecting the surface quality of the boards. Considering that the high density of the surfaces during the preparation of the board surfaces for the top surface treatments increases the quality of the board during the process of covering the surface with decor paper, it can be concluded that sanding tolerance should be minimized.

Color Changing Analysis of Laminated PBs

Among the samples with a density of 520 kg/m^3, all samples were in different color groups, except for P3 and P5. Accordingly, it can be concluded that the SL amounts, and sanded thicknesses cause differences in the colors of chipboards whose surfaces are covered with decor paper. When the color changes of the samples with a density of 560 kg/m^3 were examined according to the SL content and sanding thickness, it was determined that the P8, P11, P9, and P12 samples were in the same color group (Fig. 5). In other examples, it was concluded that the change in the SL and sanding thickness caused a color change on the board surface after melamine pressing.

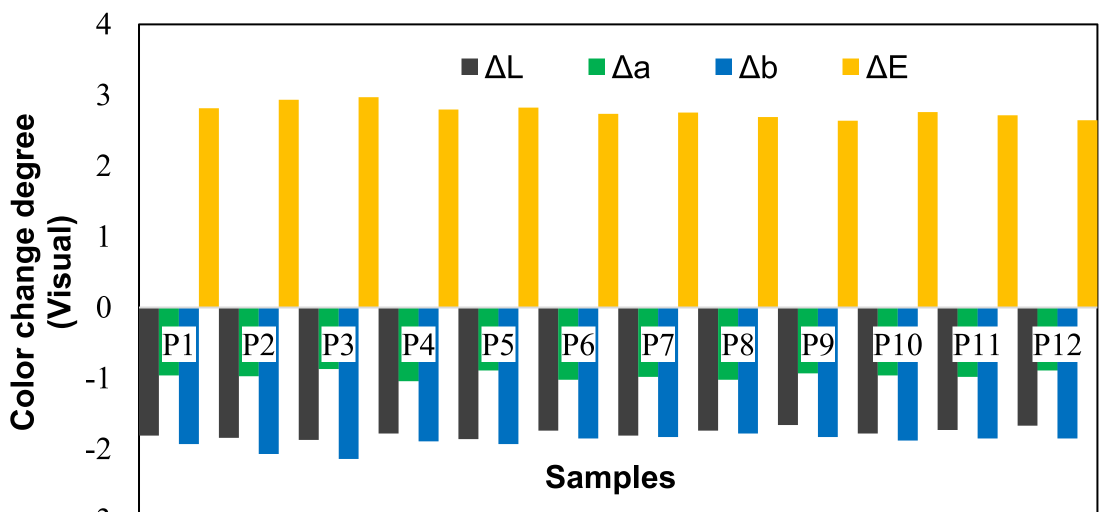

Fig. 5. Color analysis of laminated PB samples

There was a black shift of approximately 1 to 2% (ΔL) on the surfaces after melamine pressing in all the samples. The difference in color changes was not statistically significant. When the Δa (color shift between green and red) values of the samples were examined, a 1 to 1.5% shift to green was detected (Fig. 5). However, the difference was not statistically significant. When the Δb (blue-yellow color shift) values of the samples were examined, a 1 to 2% shift to a blue color was detected on the board surfaces after melamine pressing. This difference is not statistically significant.

Considering these results, it was determined that the change in SL amounts and board thicknesses after sanding did not cause a color change in boards whose surfaces were laminated with white decoration paper. The color differences on board surfaces are indeed influenced by the weight of decor paper and the type and amount of glue used during the impregnation process, rather than differences in sanding thickness or the amount of SL. Research supports that decor papers and their impregnation with adhesives, particularly melamine-formaldehyde resins or aldehyde-free alternatives, significantly affect surface properties like color uniformity, strength, and resistance to wear. Surface smoothness, bonding strength, and other physical properties are notably impacted by factors such as glue type and the physical composition of the base paper (Yu *et al.* 2020; Liang *et al.* 2023). This confirms that surface finish quality was primarily determined by these controlled variables, rather than by post-processing thickness adjustments or other mechanical factors such as the SL ratio.

Determination of Entropy Weights

All elements in the initial decision matrix were standardized and normalized to allow the use of different units of measurement. After the data were normalized, entropy weight values were determined using these equations.

Table 6. GRA Relationship Coefficients and Sorting of Alternatives

Weights	Analysis	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
0.066	MOR	0.33	0.42	0.34	0.39	0.34	0.39	0.72	1.00	0.57	0.61	0.58	0.86
0.019	MOE	0.39	0.57	0.34	0.42	0.33	0.36	0.69	1.00	0.60	0.75	0.70	1.00
0.009	IB	0.49	0.54	0.33	0.40	0.34	1.00	0.35	0.47	0.48	0.35	0.75	0.49
0.083	SS	0.38	0.41	0.36	0.37	0.33	0.45	0.93	1.00	0.74	0.61	0.83	0.83
0.02	SRy	0.36	0.45	0.36	0.45	0.38	0.33	0.72	0.47	0.49	0.58	1.00	1.00
0.121	SRk	0.33	0.60	0.59	0.70	0.64	0.54	1.00	0.51	0.39	1.00	0.82	0.82
0.024	MR	0.75	1.00	0.39	0.49	0.42	0.33	0.47	0.55	0.51	0.37	0.36	0.36
0.346	TS2h	0.33	0.48	0.70	0.89	0.80	1.00	0.46	0.44	0.81	0.62	0.61	0.61
0.013	TS24h	0.48	0.59	0.72	0.71	1.00	0.74	0.36	0.33	0.59	0.48	0.47	0.47
0.088	WA2h	0.33	0.42	0.71	0.88	0.57	0.54	0.46	0.44	1.00	0.80	0.78	0.78
0.011	WA24h	0.33	0.49	0.63	0.68	0.49	0.52	0.44	0.43	1.00	0.72	0.80	0.80
0.004	Density	0.93	0.71	0.92	0.66	1.00	0.71	0.38	0.33	0.35	0.42	0.33	0.34
0.002	ΔE	0.42	0.72	1.00	0.85	0.63	0.33	0.50	0.39	0.72	0.33	0.39	0.50
0.004	Abrasion	0.49	1.00	0.42	0.50	0.36	0.76	0.37	0.79	0.33	0.58	0.42	0.49
0.036	Tea	0.33	0.33	0.33	0.33	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00
0.018	Water	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.33	0.33	1.00
0.056	Acid	0.33	0.33	1.00	0.33	0.33	0.33	1.00	0.33	1.00	0.33	0.33	1.00
0.061	Pencil	1.00	0.50	0.33	0.50	1.00	1.00	0.50	1.00	0.50	1.00	0.50	0.50
	Degree	0.41	0.50	0.60	0.67	0.63	0.69	0.65	0.61	0.73	0.69	0.66	**0.73**
	Rank	12	11	10	5	8	3	7	9	2	4	6	**1**

GRA Relational Analysis

After the criterion weights were determined, the most appropriate alternative was determined using the Grey relational analysis. First, the data were normalized using Eqs. 2 and 3. After the data were normalized, the GRA relationship coefficient differences were calculated by taking the difference between the reference number and ordinal values using Eqs. 5 and 6, and the GRA relationship coefficients were calculated for each criterion and alternative using these values. Finally, the degree of the GRA relationship was calculated using Eq. 7, and the order of importance of the alternatives was determined (Table 6). Accordingly, the best alternative was determined to be P12, with a relationship degree of 0.731.

CONCLUSIONS

This study was motivated by the need to optimize particleboard (PB) production to reduce wood consumption while maintaining product quality, in the context of sustainability and cost efficiency. The objective was to investigate how variations in density, surface layer to core layer (SL/CL) ratio, and sanding tolerance influence PB's and laminated PB's physical, mechanical, and surface properties.

1. As the amount of SL increased, the moisture content (MC) increased. At 520 kg/m^3 PB, MC increased from 5.2% to 6.6%. At 560 kg/m^3 PB, MC increased from 5.9 to 6.7. This increased the thickness swelling values (TS2h and TS24h).
2. The increase in PB density (from 520 to 560 kg/m^3) caused an increase in moisture content (from 5.4% to 6.7%). This increased the water absorption values (WA2h and WA24h), as well as the thickness swelling.
3. Increasing density from 520 to 560 kg/m^3 significantly enhanced the mechanical strength, particularly modulus of rupture (MOR) and internal bond strength (IB), without compromising surface durability. This optimization led to a reduction in wood usage by approximately 12 to 13%, a significant outcome considering that nearly half of the production costs in particleboard manufacturing are attributed to wood.
4. The SL and sanding tolerance showed minor effects on surface properties, such as stain resistance, although abrasion resistance improved with lower sanding tolerance. Importantly, the GRA analysis identified sample P12, with a density of 560 kg/m^3 and SL content of 32%, as the optimal configuration. This sample satisfied general-purpose particleboard standards, especially IB and modulus of elasticity (MOE), while demonstrating potential for cost-effective production, though adjustments in adhesive properties are required for indoor furniture use.
5. This study offers a novel approach to balancing material efficiency with performance in particleboard production, providing a pathway for industry stakeholders to reduce costs through lower wood consumption without sacrificing mechanical or surface quality. However, this study was limited to consideration of PB density, SL amount, and sanding tolerance. Future studies could focus on refining adhesive formulations to further enhance the mechanical properties of low-density particleboards, making them suitable for a broader range of applications.

6. In the study, a low-density PB suitable for laminate surface layers was designed. This will reduce both wood consumption and costs. Manufacturers in the PB industry are conducting extensive research on this topic.

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