Foamed Thermoset Resins for Enhanced Mechanical Properties and Reduced Formaldehyde Emissions in Particleboard

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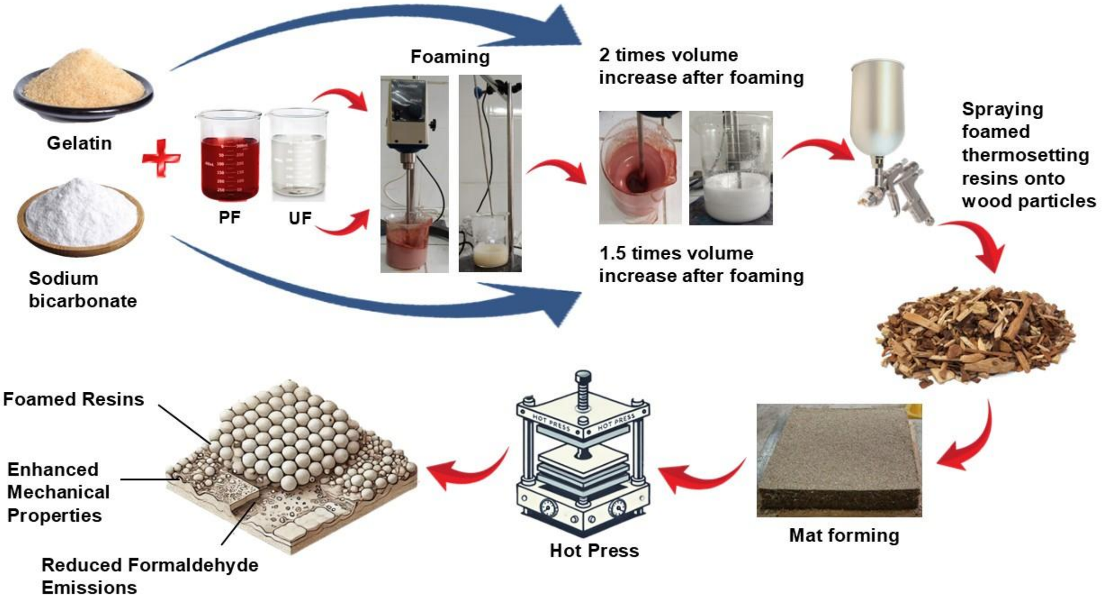
DOI: 10.15376/biores.20.2.2765-2790

GRAPHICAL ABSTRACT



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Suheyla Esin Koksal *

Urea formaldehyde (UF) and phenol formaldehyde (PF), the most commonly used thermosetting adhesives in the particleboard (PB) industry, release formaldehyde, which is harmful to both humans and the environment. This study aimed to reduce glue consumption in PB with lower formaldehyde content by foaming the glue. The UF and PF were foamed using gelatin (GL), an animal protein, and the results were compared with those performed using sodium bicarbonate (SB) foaming agent and neat (UF and PF as controls) glue. SB and GL foaming agents increased the volume of the UF and PF resins by 1.5 and 2 times, respectively. PB characterization was carried out mechanically, physically, and morphologically. A perforator analysis was performed to determine the formaldehyde content in PB. Results showed that the foaming process generally improved the mechanical properties except for 10% SB and 10% GL. Analysis showed that foaming reduced the PB moisture content and improved water absorption and thickness swelling, except for 10% SB and 10% GL. SEM analysis indicated a successful foaming process. GL and SB reduced the formaldehyde content of the PBs. In conclusion, PB can be produced using 10 to 20% less adhesive through the foaming method by GL.

DOI: 10.15376/biores.20.2.2765-2790

Keywords: Foamed adhesive; Particleboard; Phenol formaldehyde; Urea formaldehyde

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INTRODUCTION

In the last century, the human population increased rapidly and therefore the need for wooden products increased. Wood composite boards such as particle board (PB) have been developed to meet the wooden product requirement with an environmentally friendly production (Jadin *et al.* 2016; Wahab 2019). PB is one of the most used wood composites designed as an alternative to solid wood (Nishimura 2015) and is increasingly popular due to its competitive pricing and excellent properties, also because of its high demand in the construction materials market as well as decorative uses (Veigel *et al.* 2012; Ibrahim *et al.* 2022). PBs are created using wood particles, with the goal of achieving a uniform distribution of mechanical properties throughout the board (Astari *et al.* 2019). While it generally has inferior functional properties compared to solid wood, its quality can be improved by adjusting the production process to achieve the desired specifications (Rahman *et al.* 2019).

PBs are produced by molding wood particles with thermoset resins under temperature and pressure (Owodunni *et al.* 2020). Thermoset resins made from fossilderived polymers such as phenol formaldehyde (PF), urea formaldehyde (UF), melamine-formaldehyde (MF), and isocyanate (PMDI) are commonly used in PB (Youngquist 1999; Antov *et al.* 2020). Glue is a significant portion of PB production costs. Manufacturers are making efforts on gluing methods to reduce glue costs. The cost of glue depends on the way the glue is distributed on the chip surfaces (Watters 1974). The more efficiently the glue can be distributed over the wood surface, the more costs can be reduced. In the particleboard industry, the spray method is the most used method of applying glue to the wood surface (Mantanis *et al.* 2017). In this method, the glue is converted to droplets with air pressure and sprayed onto the wood surface. This method causes it to be glued in the gaps on the wood surface that have no effect on adhesion (Klauditz *et al.* 1958). Gluing the top areas where the wood particles come into contact with each other will significantly increase the gluing efficiency. Thus, it allows the use of less glue. The penetration and the wetting process of the adhesives into the wood also influence the bonding performance (internal bonding) of the produced PB (Sun *et al.* 2024). Foaming the glue can increase the gluing efficiency by increasing the volume of the glue and ensuring that the top areas of the wood particles are glued, not the gaps, and facilitating the release and even distribution of the adhesive.

This concept can be explained using an analogy involving a wire mesh and two different painting methods. In the first method, the mesh is painted using a spray at 5 bar pressure. In this case, a significant portion of the paint passes through the gaps in the mesh, resulting in substantial waste, while only a small amount adheres to the wire. In the second method, the paint is first foamed and then sprayed onto the mesh at 1 bar pressure. This approach allows the foam to adhere more effectively to the wire, minimizing waste and reducing the amount of paint required for adequate coverage.

A similar principle applies to gluing wood particles. Due to the uneven surfaces of wood particles, there are gaps and hollow areas that do not come into contact with other particles and, therefore, do not contribute to adhesion. Glue that fills these gaps is effectively wasted. By using foamed glue applied at low pressure instead of high-pressure spray, the glue can be distributed more efficiently over the surfaces of the wood particles. This method reduces waste and enhances the overall gluing efficiency for rough wooden surfaces

UF and PF resins contain formaldehyde and release it over time, and formaldehyde also is considered a carcinogenic substance for humans (IARC 2004). Formaldehyde has negative impacts on biological systems and the environment (Cogliano *et al.* 2005). Consequently, there is a growing need to reduce formaldehyde content and develop environmentally friendly alternatives. Foaming the glue increases the gluing efficiency. This allows less glue to be used in PB. Reducing the glue content in PB means reducing the formaldehyde released. Increasing the gluing efficiency both reduces costs and ensures healthier production. Böhm *et al.* (2012) investigated the formaldehyde emission from various solid wood, plywood, chipboard and flooring products produced using PF and a foaming agent (oxyethylene castor oil and mixture of non-ionic tensides) and reported that plywood produced with PF had lower formaldehyde emission than other wood materials (according to EN 717-2, $P < 0.001$). In addition, formaldehyde emissions of boards produced with PF have been studied (Chen *et al.* 2024; Jia *et al.* 2020; Yu *et al.* 2018). The amount of foaming agent used and its price are also important in reducing gluing costs. In this respect, the amount of foaming agent added to the glue can be calculated using Eq. 1. to determine how much it will reduce costs. There are four unknowns in the equation. For example, if one knows the price of glue and foaming agent and the percentage of agent that is being added to the glue, then one can calculate the minimum percentage improvement (% less glue usage) that needs to be achieved in order for the cost not to change. In a PB factory that uses an average of 100 tons of glue per day, a glue saving of 15 to 20% will more than cover the factory's foaming agent and additional workload cost items.

$$\frac{Glue\ (kg)\ price}{Foaming\ agent\ (kg)\ price} = \frac{Foaming\ agent\ concentration\ in\ glue\ (\%)}{Glue\ reducing\ rate\ (\%)} \tag{1}$$

For this reason, glue foaming can make a significant contribution to production by both reducing formaldehyde emissions at the point of use and providing lower costs, making the process less harmful and more sustainable. Because foamed glue can cover more wood surface area, this increases bonding efficiency.

The glue can be foamed using natural (Sellers Jr 1988; Kelleci *et al.* 2022) and synthetic (Bi *et al.* 2021) foaming agents, thus both producing low-density boards and reducing glue consumption. Although foamed adhesives offer an environmentally friendly and clean production alternative in board production, limited research has been conducted on this issue. Successful results have been reported in the production of particleboards using liquid Freon 12 by Watters (1974) and wheat flour and animal blood by Sellers (1988). In other work, Bi and Huang (2021) and Boruszewski *et al.* (2022) used chemical agents (azodicarbonamide, 5-phenyl-1H-tetrazole, *p*-toluenesulfonyl hydrazide) to obtain lightweight particleboards. In these methods, foaming agent was added to the glue and mixed mechanically or foamed with heat under a hot press. In the present study, the glue was foamed with a different method.

In recent years, there has been increased interest in eco-friendly, sustainable, and renewable alternative adhesives due to the drawbacks of thermoset adhesives (Antov *et al.* 2020). Thermoset adhesives, despite their strong bonding performance and resistance to heat and chemicals, have significant drawbacks, including brittleness and poor recyclability, which limit their environmental sustainability (Gangil *et al.* 2024, Morici and Dintcheva 2022). Bio-based adhesives such as lignin, starch, and tannin have gained significant attention for this purpose (Cavdar *et al.* 2008; Mary *et al.* 2024; Navarrete *et al.* 2010; Pepin *et al.* 2024; Wang *et al.* 2015; Yang *et al.* 2015; QiaoZhi Bang *et al.* 2016; Gonultas 2018; Nath *et al.* 2018). But these adhesives are not resistant to water and moisture. Konnerth *et al.* (2009) produced 13 mm PB using animal protein glue (AG) produced from bone and compared the results with MUF (melamine-urea-formaldehyde). While the internal bond (IB) strength with AG was 0.56 MPa and the bending strength was 10.1 MPa, in MUF these values were 0.80 and 13.5 MPa, respectively. Although AG resistances are low, they meet the TS EN 312 (2005) standard. However, the amount of swelling is high (13.6%) and does not meet the thickness swelling standard (13.6% >TS EN 317 (1999)). Bio-based adhesives face challenges in fully replacing thermoset adhesives due to their lower water resistance and bonding strength compared to thermoset adhesives (Antov *et al*. 2020). It can be said that it would be more effective to use thermoset and bio adhesives by mixing them. Kelleci *et al*. (2022) blended egg white (EW) containing ovalbumin, a bio-based adhesive, with UF in certain proportions and used it to manufacture the PB. They found that the addition of EW increased the IB force and did not change the amount of swelling. This is a promising result.

In this study, cattle gelatin (GL) and sodium bicarbonate (SB) were used as foaming agents. Gelatin is a biopolymer obtained by the hydrolysis of collagen protein in animal tissues under controlled conditions. About 46% of gelatin is obtained from pig skin, 29.4% from cattle skin, 23.1% from bone, and 1.5% from other sources (Schrieber *et al.* 2007). Gelatin is used extensively in the food industry for purposes such as gelling, thickening, water binding, emulsification, foam formation, and film formation (Karim *et al.* 2008). Additionally, gelatin is known for its ability to enhance the mechanical and adhesive properties of a composite matrix (Wang *et al.* 2016). GL, being a protein, is a good wood adhesive and foaming agent. Its organic structure, which consists of amino acid chains with functional groups such as amine ($-NH_2$) and carboxyl (-COOH), allows it to react with formaldehyde through Schiff base formation and other nucleophilic reactions, effectively capturing free formaldehyde and reducing its emissions (Haddar *et al.* 2012). This property makes gelatin an eco-friendly additive in wood-based adhesives and composites (Ghani *et al.* 2018; Kelleci *et al.* 2022).

Sodium bicarbonate is a well-known foaming agent widely used in various industries due to its environmentally friendly properties. It is often referred to as a 'green-blowing foaming agent' because it decomposes upon heating to produce harmless byproducts, namely carbon dioxide (CO_2) and water (H_2O), depending on the time and temperature (Heda *et al.* 1995; Fauzi *et al*. 2015). This makes it a sustainable choice compared to synthetic foaming agents. Bednarczyk and Boruszewski (2022) used SB as a foaming agent in the production of lightweight PBs, and the application was found to significantly increase the IB strength of the boards. In our study, SB was used to foam UF and PF glue, and our aim was not to produce low-density PB but to foam the glue and enable it to cover more wood particle surface area.

This study aimed to foam the UF and PF by adding GL as an organic foaming agent and SB as an inorganic foaming agent. In the foaming process, unlike previous studies in the literature, GL was first foamed, and glue was added into the foamed GL and mixed. In this way, a more homogeneous glue foam was obtained. The goal is to decrease glue consumption in PB.

EXPERIMENTAL

Materials

Black pine (*Pinus nigra* Arnold.) wood particles were used to produce the PBs samples. The foaming agents, SB was purchased from local market (CAS Number: 144-55-8, Purity: ≥99%), GL (200 bloom) produced by alkaline method was supplied from Gerede gelatin factory in Türkiye. Urea formaldehyde (UF) resin and ammonium sulfate (AS) hardener were supplied by Yildiz Entegre Wood Industry Inc., and PF resin was supplied by GENTAS Laminate Industry Inc. The moisture content (MC) of the particles was calculated as 15% before the pressing process, whereas 12% after pressing according to Eq. 2. Some properties of the materials used in PB are given in Table 1.

$$MC(\%) = \frac{M_h - M_0}{M_0} \times 100 \tag{2}$$

Here, M_h is humid chip mass, and M_0 is oven-dry chip mass in unit grams.

Table 1. Some Properties of Materials used in PB

Materials	Status	Solid Content (%)	Density (g/cm^3)	pH	Viscosity (cp)
UF	Solution	65	1.284	7.4	300
PF	Solution	44	1.200	7.2	280
AS	Solution	30	1.154	5.4	12
GL	Solution	30	1.05	7.1	3500
SB	Solution	30	1.15	8.4	2900
Wood	Solid	98	0.21	5.1	solid

Preparation of Foamed UF/PF

In the glue foaming process with GL, an aqueous solution was first prepared by adding 30 g of GL to 70 g of pure distilled water in a 250 mL glass container. The container was then immersed in another 500 mL glass container containing 300 mL boiling water. GL was dissolved over low heat (70 ºC) by manually stirring with a glass rod. Immediately after the GL melted (60 s), it was formed into a foam by mixing with a mechanical mixer at 3000 rpm for 60 s (Fig. 1e). About 500 mL of the foamed GL was transferred to another glass container and 570 g of UF (65% concentration) and 15 g AS (25% concentration) were added and blended (1000 rpm) with a mechanical mixer (WIGGENS WB3000-D) for 60 s and GL/UF foam glue was prepared. In this way, the volume of glue was increased by 2 times. The same process was repeated using PF glue.

In the foaming process with SB, 30 g of SB was added to 70 g of pure water in a 250 mL glass container and blended at 3000 rpm for 5 min. The mixture was transferred to another 500 mL glass container and 570 g of UF (65% concentration) and 15 g AS (25% concentration) were added. The mixture was blended by a mechanical blender at 3000 rpm for 5 min and SB/UF foamed glue was prepared. In this way, the volume of the glue was increased by 1.5 times. The same process was carried out for PF glue. The foaming agent/glue mixtures were prepared in two concentrations (5% and 10%). PF and UF glues were used in two different ratios (10% and 12%) according to the dry chip weight. Prepared mixture samples are given in Table 2. The mechanical blending process caused micro air bubbles to form in the glue mixture, resulting in an increase in the volume of UF and PF by about 1.5 to 2 times. The prepared glue was applied to the wood particles using an air gun which has 3 mm nozzle (Fig. 1f). A wide nozzle was chosen to prevent the foam from deflating. Also, the foamed UF and PF (100 g) were poured onto a Teflon plate and allowed to dry for 7 days for analyzing with a scanning electron microscope (SEM).

Preparation PB Samples

Black pine bark was peeled manually (Fig. 1a), and then the wood was mechanically chipped. Wood particles were obtained using a planer with a 0.5 mm knife gap, resulting in wood particles with a thickness of 0.25 to 1 mm, a width of 17 to 20 mm, and a length of 75 to 100 mm from the chipper (Figs. 1b, and 1c). The wood particles were left to dry naturally (at room temperature, 22 °C) for one week. Air-dried particles were then placed in an oven at 105 °C, and the moisture content of the wood particles was reduced to 2% (Fig. 1d).

Fig. 1. PB manufacturing process: a) Wood sample, b) notch on wood, c) wood chipping, d) drying, e) glue preparation, f) gluing, g) mat forming and cold press, h) hot press, i) produced PB, and j) test samples

PB samples were formed with dimensions of 16 × 400 × 400 mm and a density of 650 ±10% kg/m^3. The wood particles were oriented in three layers (0°/90°/0°) by hand to form the PB mat. The amount of glued wood particles was calculated according to the PB sample volume to be produced, and the sample density was targeted as 650 kg/m^3. In the pressing process, the sample thicknesses were adjusted by placing 16 mm x 16 mm x 500 mm iron wedges on the edges of the press. Since density is one of the most important factors affecting the physical and mechanical properties of the PB (Wong *et al.* 1999; Sackey *et al.* 2008), care was taken to avoid density fluctuations in PBs. Two solid UF and PF resins were prepared at 10% and 12% (mass of resin solids/mass of dry wood particles), respectively. Table 2 shows the proportions of UF and PF resins in the PBs.

The glued wood particles were poured into the mold, where a 2 mm metal plate was placed under the PB mat. After removing the mold, a second 2 mm metal plate was placed over the PB mat (Fig. 1g). Subsequently, the PB mat was placed in a single flat hot press (Fig. 1h). The temperature on the lower and upper heating plates was set to 190 °C for UF resin and 135 °C for PF resin because the PF was the type of glue used for plywood production, so it was pressed at 135 degrees for plywood production. The PB mat was pressed for 540 s at 24.5 bar for PF (Maulana *et al.* 2021) and for 360 s at 32 bar for UF

(Kelleci *et al.* 2022). After pressing, the edges of the PBs were cut to 370 x 370 mm with a circular saw (Fig. 1i), and samples were prepared according to the standards (Fig. 1j). The PBs boards were acclimated for two days at room temperature before being cut with a circular saw, as shown in Fig. 2, during preparation for analysis.

Table 2. Phenol Formaldehyde and Urea Formaldehyde Formulations

Solid Resin/wood (%)	Sample Code	Foaming Agents	CL[1] (g)	UF[2] (g)	PF[3] (g)	AS[4] (g)	SB[5] (g)	GL[6] (g)	Produced board (Boards)
10 UF	CTRL10U	Control	1600	220	-	15	-	-	7
	5S10U	5% Sodium bicarbonate	1600	220	-	15	7	-	7
	10S10U	10% Sodium bicarbonate	1600	220	-	15	14	-	7
	5G10U	5% Gelatin	1600	220	-	15	-	7	7
	10G10U	10% Gelatin	1600	220	-	15	-	14	7
12 UF	CTRL12U	Control	1600	350	-	20	-	-	7
	5S12U	5% Sodium bicarbonate	1600	350	-	20	10	-	7
	10S12U	10% Sodium bicarbonate	1600	350	-	20	20	-	7
	5G12U	5% Gelatin	1600	350	-	20	-	10	7
	10G12U	10% Gelatin	1600	350	-	20	-	20	7
10 PF	CTRL10P	Control	1600	-	220	-	-	-	7
	5S10P	5% Sodium bicarbonate	1600	-	220	-	7	-	7
	10S10P	10% Sodium bicarbonate	1600	-	220	-	14	-	7
	5G10P	5% Gelatin	1600	-	220	-	-	7	7
	10G10P	10% Gelatin	1600	-	220	-	-	14	7
12 PF	CTRL12P	Control	1600	-	350	-	-	-	7
	5S12P	5% Sodium bicarbonate	1600	-	350	-	10	-	7
	10S12P	10% Sodium bicarbonate	1600	-	350	-	20	-	7
	5G12P	5% Gelatin	1600	-	350	-	-	10	7
	10G12P	10% Gelatin	1600	-	350	-	-	20	7

[1]: Black pine wood particles (1.5% humidity), [2]: 65% solid urea-formaldehyde (UF) solution, [3]: 44% solid phenol-formaldehyde (PF) solution [4]: 30% solid ammonium sulfate (AS), [5]: Dry powder form sodium bicarbonate, [6]: Cattle gelatin dry powder form.

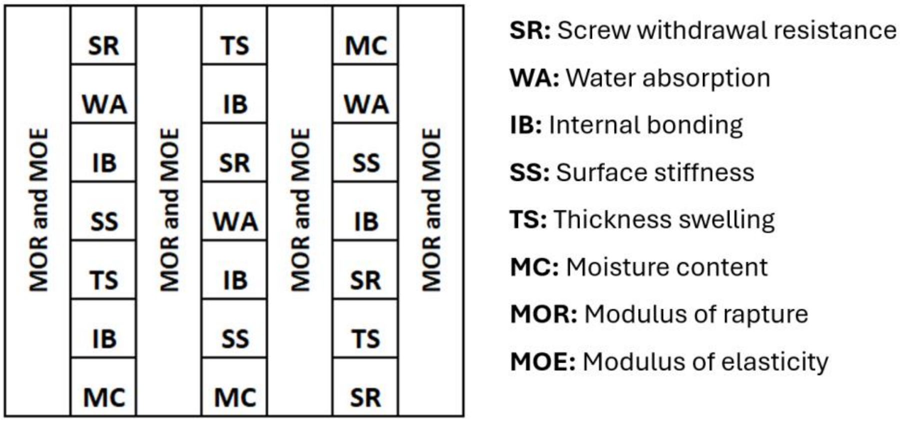

Fig. 2. 16 mm PB cutting plan for physical and mechanical characterizations

Methods

The dimensions of the test specimens were prepared in accordance with TS EN 325 (2012) and TS EN 326-1 (1999). The test specimens were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity (RH) for two weeks after being cut. In this study, the samples were characterized mechanically, physically, and morphologically, as it was aimed to produce particleboards (PB) that meet the required standards while using less glue and reducing formaldehyde emissions.

Thickness swelling (TS) and water absorption (WA) tests were conducted in accordance with TS EN 317 (1999). For these tests, specimens were immersed in water for 24 hours to evaluate their dimensional changes. These tests were essential for assessing the water resistance and dimensional stability of the particleboards in wet conditions.

Moisture content (MC) was measured according to TS EN 322 (1999). Samples were oven-dried at 103 ± 2 °C until constant weight was achieved, and the moisture content was calculated based on the mass difference before and after drying.

Density profile analysis was carried out using a GreCon Density Profiler, employing an X-ray-based measurement process. This method provided detailed information on the density variations throughout the thickness of the panels, with results recorded.

The overall density of the panels was measured according to TS EN 323 (1999) using 50 mm × 50 mm specimens. Density was calculated as the ratio of the oven-dry mass of the specimens to their volume, with the volume determined from the specimen's dimensions. This test ensured precise evaluation of the density distribution within the panels.

The modulus of elasticity (MOE) and modulus of rupture (MOR) were determined through a three-point bending test conducted in accordance with TS EN 310 (1999). These tests were performed using a Shimadzu AGS-X Universal Testing Machine at a crosshead speed of 5 mm/min, with eight specimens tested for each group. The MOE provided information about the stiffness of the particleboards, while the MOR evaluated their bending strength.

Internal bond strength (IB) was assessed according to TS EN 319 (1999) using a Shimadzu AGS-X Universal Testing Machine. The tests were conducted at a crosshead speed of 5 mm/min to evaluate the adhesive strength between particles within the boards.

Screw resistance (SR) was measured following TS EN 320 (2011). This test determined the mechanical performance of the panels by measuring the force required to insert and remove screws from the boards.

Morphological characterization was conducted using a JEOL JSM-7600F Field Emission Scanning Electron Microscope (SEM), operating at 15 kV. Before imaging, the samples were sputter-coated with a thin layer of palladium to enhance conductivity and improve image resolution. SEM analysis provided detailed observations of the matrix structure and foam formations.

Formaldehyde content analyses were performed using the perforator method according to TS EN ISO 12460-5 (2016). In this method, small wood-based samples were extracted with boiling toluene, and the formaldehyde released into the solution was quantified using spectrophotometry. The results were expressed in milligrams per 100 grams of dry mass.

The statistical evaluation of the results was performed using SPSS software. A one-way analysis of variance (ANOVA) with a significance level of $p < 0.05$ was applied to identify statistically significant differences between the samples. Post-hoc comparisons among groups were conducted using Duncan's test to further evaluate group differences.

RESULTS AND DISCUSSION

Physical Properties

The foaming process with the addition of SB and GL had little effect on densities. In this study, it was aimed to reduce glue consumption in PB and, consequently, decrease its formaldehyde content. Therefore, PBs were produced at a density of 650 ± 20 kg/m^3, and density was not emphasized much. Some studies have reported that the SB foaming agent reduced the density of the board (Zhao *et al.* 1995; Jiang *et al.* 2016; Bi and Huang 2021). While this study and the afore-mentioned studies were similar in terms of foaming agents, their aims differed, as this study aimed to reduce the UF and PF contents of PB.

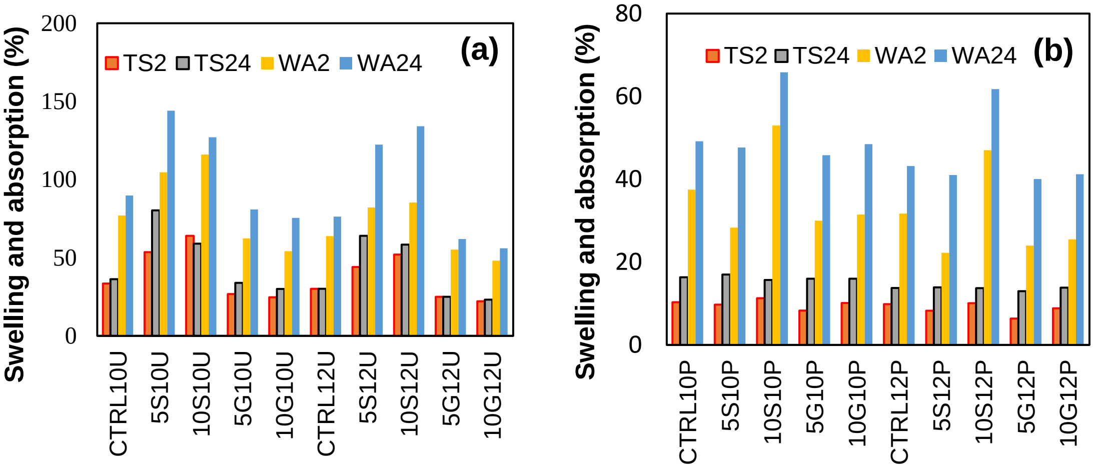

Fig. 3. Thickness swelling and water absorption of foamed PB: (a) produced with UF, and (b) produced with PF

When Figs. 3a and 3b are examined, it is apparent that SB increased the WA amount. In contrast, the samples containing GL exhibited lower WA and TS values compared to those with SB. This difference may be attributed to the nature of the two additives. Since SB is a salt consisting of a sodium cation (Na^+) and a bicarbonate anion (HCO_3^-), it may have facilitated water uptake and increased the swelling of PB. On the other hand, GL was pre-saturated with water during solution preparation, which may have reduced its tendency to absorb additional water from the surrounding environment. Furthermore, the proline amino acid in the structure of GL tends to form hydrogen bonds with water molecules (Erge *et al.* 2016), which may have contributed to a more stable water interaction, leading to lower swelling compared to SB. As a result, while SB led to higher WA and TS values, GL exhibited relatively lower values in comparison. It was determined that the WA increased at the same rate in 10S10P and 10S12P samples whose densities decreased when foamed with SB (Fig. 3b).

When the moisture content of PBs was examined, it was determined that SB decreased the moisture content, whereas GL increased it. This observation can be attributed to the differing chemical and physical properties of these additives. SB promotes the release of water vapor during the foaming process due to its decomposition, which produces carbon dioxide (CO_2) and water (H_2O), thereby reducing the overall moisture content. In contrast, GL is a protein-based material with hydrophilic properties, meaning it tends to absorb and retain moisture from its surroundings. This leads to an increase in the moisture content of PBs when GL is used. The MC for all samples was within the standards (TSE EN 322, 1999). All PBs produced with foamed UF and PF were of normal density according to standards (low density < 590 kg/m^3 < normal < 800 kg/m^3 < high density) (TSE EN 323, 1999).

It was determined that all TS results were below the standards with foamed UF (TSE EN 317, 1999). This may be related to the amount of hardener (AS) used in UF. In this study, the AS/UF ratio was 3.1% (solid/solid concentration), whereas Kelleci *et al.* (2022) used AS at levels exceeding 10% and reported increased WA and TS values in PBs. The lower AS concentration in our study (3.1%) likely contributed to the reduced WA and TS values observed, highlighting a contrast with the findings of Kelleci *et al.* (2022).

When the density profiles (Fig. 4) were examined, surface densities were between 800 and 910 kg/m^3 in foamed UF samples (Figs. 4a, 4b) and 800 and 850 kg/m^3 in foamed PF samples (Figs. 4c, 4d). The high surface densities have a positive effect on the modulus of rupture (MOR) strength of the PB (Istek *et al.* 2017). Although the surface densities of PBs produced with foamed UF were higher than the densities of PBs produced with foamed PF, their MOR strengths were lower (Tables 3 and 4). This was caused by the fact that the adhesion strength of PF glue was higher than UF. A significant difference in peak and core densities has a negative impact on TS and WA (Wong 1998). When Fig. 4 is examined, it can be seen that the density distributions of PBs produced with foamed PF were more stable (Figs. 4c, 4d) and the density distributions of PBs produced with foamed UF (Figs. 4a, 4b) were more scattered. This situation caused more TS and WA in foamed UF samples.

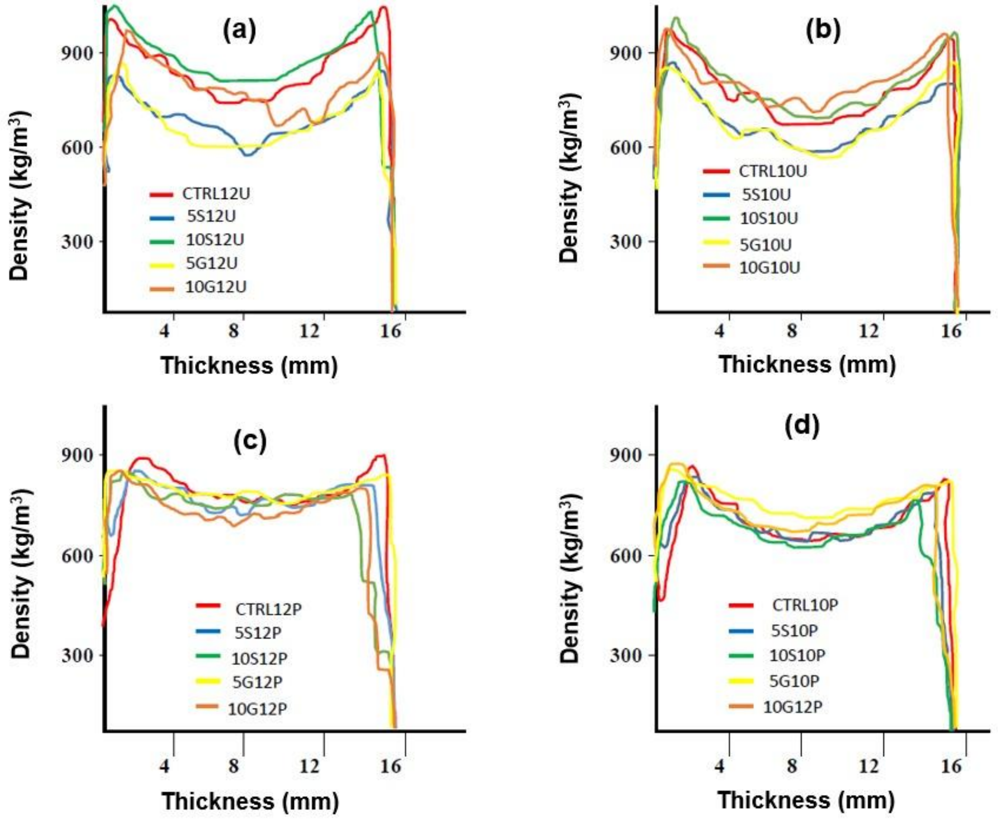

Fig. 4. Density profile of foamed PBs produced with 12% UF (a), 10% UF (b), 12% PF (c), 10% PF (d)

The moisture content of the wood particles was 17% just before the hot-pressing process. Interaction of heat, moisture, and pressure causes non-uniform deformation of elements during the hot-pressing process. This causes an uneven density distribution along the board's thickness, resulting in a 'U-shape' profile. The highest density can be found near the board edges, while the lowest density can be found in the core region (Wong *et al.* 1999). The qualitative impact of the density profile on board properties has been extensively discussed, but the specific formation process and its effects on board performance remain unknown. The presence of a vertical density gradient has been observed to result in higher bending strength but lower internal bond as well as interlaminar shear (Kelly 1977). A steep density gradient in low-density particleboard can cause shear failure before bending failure, lowering the MOR (Kawai and Sasaki 1986). Overall, the density profile is critical in determining the board's mechanical and physical properties (Wong *et al.* 1999).

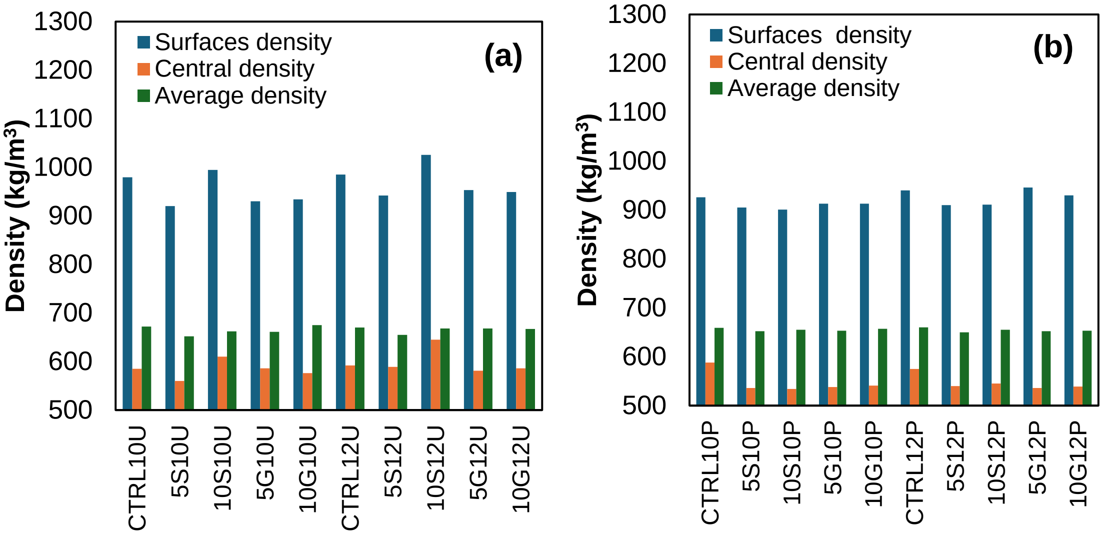

Fig. 5. Density profile of PBs foamed by UF (a); and foamed by PF (b)

One-way Anova and Duncan statistical analysis results of the density profile are given in Table 3. No significant difference was found in the PF samples except for the average density (P=0.818). When the Duncan analysis was examined, it was determined that the profile densities of the UF samples showed a more scattered grouping than the PF samples.

When Fig. 5b is examined, it is apparent that the central density was lower than the surface density and the average density for both UF and PF resin. PF is more resistant to water than UF resin (Ulusoy and Peker 2019). This has resulted in more WA and TS in PBs produced with UF. Also, it is seen in Fig. 5b that the density of the CTRL12P sample was higher than the other samples. This was caused by the high humidity of the CRTL12P sample (Table 4). The high humidity of the CRTL12P sample allowed the hot press to compress the PB mat further, resulting in reduced thickness and increased density. This elevated humidity also enabled lower pressing pressures and temperatures during PB production. However, the high moisture content led to more water vapor being released from the PB, which caused splitting in the middle of the mat when the press was opened. Additionally, this increased vapor discharge prolonged the press time, further impacting the process.

Table 3. Density Profile of PB Samples

Samples	Surfaces density	Central density	Average density	Samples	Surfaces density	Central density	Average density
	P: 0.001*	P: 0.001	P: 0.041		P: 0.001	P: 0.001	P: 0.818
CTRL10U	980 d (±3)	585 bc (±5)	672 c (±7)	**CTRL10P**	926 de 3(±7)	588 b (±9)	659 a (±7)
5S10U	920 a (±5)	560 a (±5)	652 a (±9)	**5S10P**	905 ab (±5)	536 a (±8)	652 a (±9)
10S10U	995 d (±5)	610 d (±2)	662 abc (±11)	**10S10P**	901 a (±4)	534 a (±4)	655 a (±5)
5G10U	930 bc (±7)	586 c (±3)	661 abc (±6)	**5G10P**	913 ab (±4)	538 a (±4)	653 a (±6)
10G10U	934 ab (±4)	576 ab (±5)	675 c (±6)	**10G10P**	913 bc (±5)	541 a (±6)	657 a (±5)
CTRL12U	985 d (±5)	592 c (±5)	670 bc (±6)	**CTRL12P**	940 ef (±5)	575 b (±5)	660 a (±5)
5S12U	942 bc (±6)	589 bc (±13)	655 ab (±8)	**5S12P**	910 ab (±2)	540 a (±10)	650 a (±5)
10S12U	1026 e (±8)	645 e (±5)	668 c (±5)	**10S12P**	911 ab (±3)	545 a (±5)	655 a (±3)
5G12U	953 c (±6)	581 bc (±6)	668 abc (±6)	**5G12P**	946 f (±3)	536 a (±5)	652 a (±9)
10G12U	949 c (±7)	586 bc (±5)	667 abc (±16)	**10G12P**	930 cd (±7)	539 a (±7)	653 a (±5)

*: (P) Statistical significance

Table 4. Foamed UF Mechanical and Physical Properties

Samples	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)	SR-Y (N/mm)	SR-K (N/mm)	MC (%)	TS (2 h)	TS (24 h)	WA (2 h)	WA (24 h)	DN (kg/m^3)
	*P: 0.01	P: 0.01	P: 0.04	P: 0.01	P: 0.01	P: 0.01	P:0.01	P: 0.01	P: 0.01	P: 0.01	P: 0.01
CTRL10U	20.0 cd (±2.7)	3849 a (±396)	0.29 ab (±0.04)	85 c (±7)	654 a (±8.2)	5.7 c (±0.16)	33 b (±3.6)	36 b (±2.3)	109 c (±4.6)	77 c (±9.6)	672 a (±25)
5S10U	25.0 ef (±1.8)	5528 b (±358)	0.28 ab (±0.02)	63 a (±5)	764 d (±6.4)	5.4 b (±0.10)	54 d (±4.6)	80 d (±6.8)	93 d (±5.1)	105 d (±17)	652 a (±19)
10S10U	12.4 a (±1.5)	3695 a (±725)	0.29 ab (±0.02)	60 a (±1)	722 c (±3.1)	5.1 a (±0.23)	64 e (±5.3)	59 c (±7.6)	95 d (±9.6)	116 d (±10.6)	662 a (±41)
5G10U	20.4 cde (±3.5)	3278 a (±395)	0.33 bc (±0.17)	90 cd (±2)	682 b (±6.9)	7.3 f (±0.23)	27 ab (±1.6)	34 ab (±4.2)	109 b (±3.5)	62 bc (±6.5)	661 a (±22)
10G10U	16.5 abc (±5.7)	3438 a (±636)	0.26 a (±0.018)	82 c (±1)	665 a (±3.1)	7.8 g (±0.12)	25 ab (±1.5)	30 ab (±2.2)	116 ab (±1.8)	54 abc (±2.1)	669 a (±1.7)
CTRL12U	22.0 cde (±2.0)	6541 c (±485)	0.32 bc (±0.06)	94 d (±0.6)	756 d (±2.8)	6.3 e (±0.16)	30 ab (±1.7)	30 ab (±1.7)	118 b (±2.0)	64 abc (±2.3)	670 a (±1.7)
5S12U	27.8 bc (±2.3)	7976 d (±832)	0.31 bc (±0.05)	72 b (±1.2)	863 h (±3.1)	6.1 de (±0.24)	40 c (±1.2)	64 c (±2.4)	91 c (±1.9)	82 d (±3.0)	655 a (±3.6)
10S12U	14.6 f (±1.7)	4094 a (±548)	0.33 bc (±0.05)	68 ab (±1.2)	823 g (±2.8)	5.9 cd (±0.27)	52 cd (±1.9)	58 c (±1.3)	86 c (±2.8)	85 d (±2.0)	665 a (±2.2)
5G12U	27.6 f (±5.9)	9552 e (±958)	0.36 c (±0.04)	98 d (±1.1)	803 f (±2.1)	8.2 h (±0.41)	25 ab (±1.0)	25 ab (±0.9)	101 ab (±2.2)	55 ab (±2.6)	668 a (±3.2)
10G12U	18.2 bcd (±1)	3988 a (±879)	0.30 ab (±0.03)	93 d (±2.1)	782 e (±1.9)	8.7 i (±0.25)	22 a (±1.4)	23 a (±0.9)	98 a (±2.1)	48 a (±1.1)	667 a (±2.6)
Standard	> 11.5	> 1500	> 0.35	> 50	> 600	6 ±1	≤ 8%	≤ 20	None	None	610 ±10

*: (P) Statistical significance

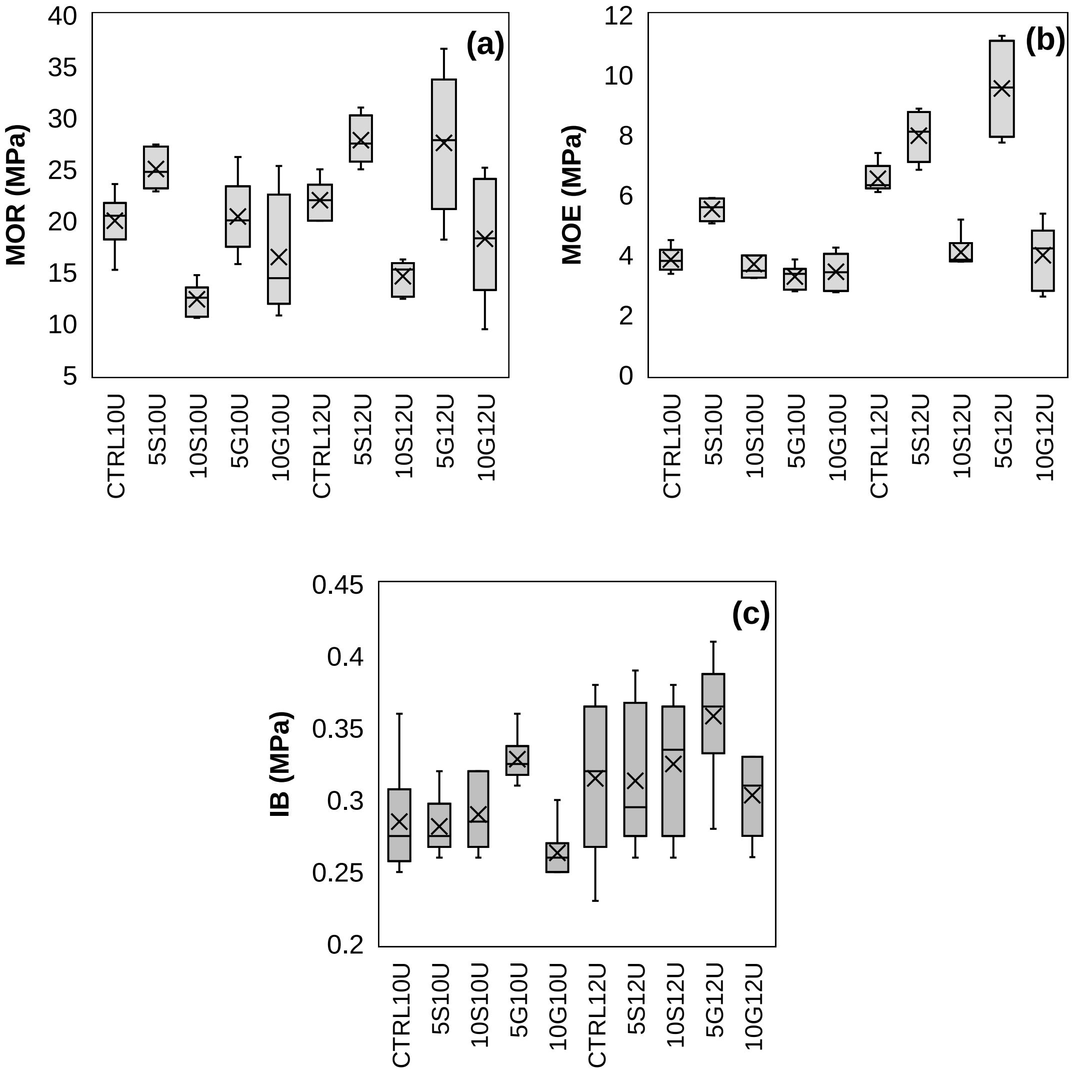

Fig. 6. (a) MOR (b) MOE, (c) IB strength of sample produced with foamed and unfoamed (CTRL) UF

Mechanical Properties

The mechanical and physical analysis results of the foamed UF samples are presented in Table 4, and those of the foamed PF samples are shown in Table 5. The mechanical and physical properties of the samples with foamed PF were superior to those of UF. Foaming with 5% SB and 5% GL increased the MOR strength. However, foaming with 10% SB and 10% GL reduced the MOR strength (Fig. 6a). This phenomenon can be attributed to the excessive use of SB and GL, which may interfere with the adhesive's chemical structure and bonding mechanism. High amounts of SB produce excessive carbon dioxide during foaming, reducing the degree of polymerization and weakening the bond strength. Similarly, an excess of GL may disrupt the crosslinking density within the adhesive matrix. The proteinaceous structure of gelatin, when used in high concentrations, can create inhomogeneities and weak zones within the matrix, negatively impacting mechanical performance. Similar results were found in the MOE analyses (Fig. 6b), where an increase in MOR strength led to a corresponding increase in MOE.

The IB strength increased with 5% GL compared to the control sample (Fig. 6c), but foaming with SB did not affect the IB strength in UF and PF glue. When the GL content was increased from 5% to 10%, the IB strength decreased.

In this study, the primary goal was to reduce glue consumption by enhancing bonding efficiency through the foaming process. The results indicate that adding 5% GL effectively achieved this objective. However, foaming UF and PF with SB did not yield a positive effect on the IB strength. In contrast, a similar study by Bednarczyk and Boruszewski (2022) demonstrated that using foamed PF resin with SB improved the IB strength of particleboards. This discrepancy can be attributed to the differences in the board densities studied. While Bednarczyk and Boruszewski focused on low-density (550 kg/m^3) board production, the present study produced higher-density boards (650 kg/m^3). This variation in board density likely influenced the IB strength outcomes. Specifically, foaming the glue with SB proved ineffective for boards with densities exceeding 650 kg/m^3. Therefore, it can be concluded that the foaming process with SB is more suitable for producing boards with densities below 650 kg/m^3.

Different results have been reported in different studies for mechanical strength in the foaming process. In the work of Soares *et al.* (2013), the incorporation of foaming agents led to a reduction in the density of the PP/wood flour composites. However, this decrease in density was accompanied by a significant decrease in modulus and tensile strength, primarily attributed to the presence of voids or holes within the composite. Therefore, while higher amounts of foaming agents contributed to lower density, they also resulted in a decrease in both the modulus and tensile strength of the composites (Soares *et al.* 2013).

Table 5. Foamed PF Mechanical and Physical Properties

Samples	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)	SR-Y (Newton)	SR-K (Newton)	MC (%)	TS (2 h)	TS (24 h)	WA (2 h)	WA (24 h)	DN (kg/m^3)
	*p-value: 0,01	P: 0,01	P: 0,04	P: 0,01	P: 0,01	P: 0,01	P:0,01	P: 0,01	P: 0,01	P: 0,01	P: 0,01
CTRL10P	28.2 bc (±2,4)	3957 bc (±152)	0.31 bcd (0.02)	119 bcde (±7)	858 a (±9.2)	9.2 bc (±0.23)	10.3 bc (±0.27)	16.3 c (±1.5)	37.5 d (±2.8)	49.2 c (±3.0)	659 a (±5.0)
5S10P	35,2 de (±4,6)	4763 de (±261)	0.29 ab (±0.02)	102 ab (±5)	1132 ab (±6.2)	8.6 ab (±0.23)	9.8 bc (±0.29)	17.0 c (±2.1)	28.3abc (±3.7)	47.7bc (±3.2)	652 a (±4.5)
10S10P	20,2 a (±2,3)	3221 a (±139)	0.33 bcd (±0.02)	93 a (±1)	995 ab (±4.2)	8.5 a (±0.18)	11.3 c (±0.11)	15.7 bc (±1.3)	53.0 e (±4.4)	65.8 d (±3.6)	655 a (±6.1)
5G10P	31.3 cd (±3.9)	4639 de (±49)	0.36 d (±0.03)	111 abcd (±2)	960 ab (±6.9)	8.3 a (±0.29)	8.3 ab (±0.26)	16.0 c (±1.7)	30.0 bc (±3.7)	45.8abc (±2.4)	653 a (±6.8)
10G10P	28.2 bc (±2.5)	4332 cd (±136)	0.25 a (±0.02)	109 abc (±1)	891 a (±2.9)	8.4 a (±0.17)	10.1 bc (±0.29)	16.0 c (±1.7)	31.5 cd (±2.6)	48.5c (±3.2)	657 a (±7.1)
CTRL12P	31.5 cd (±5.4)	4288 cd (±478)	0.35 bcd (±0.04)	134 e (±0.6)	992 ab (±23)	10.7 d (±0.97)	9.8 bc (±2.17)	13.8 ab (±2.1)	31.7 cd (±5.8)	43.2abc (±9.2)	660 a (±6)
5S12P	39.0 e (±5.2)	5147 e (±341)	0.34 bcd (±0.03)	128 cde (±1.2)	1273 b (±20)	9.6 c (±0.92)	8.3 ab (±3.06)	13.9 ab (±1.4)	22.2 a (±4.8)	41.0ab (±7.3)	650 a (±11)
10S12P	24.2 ab (±5.3)	3631 ab (±940)	0.35 cd (±0.05)	106 ab (±1.2)	1173 ab (±10)	9.6 c (±0.51)	10.1 bc (±1.12)	13.7 ab (±1.2)	47.0 e (±5.7)	61.8 d (±3.3)	655 a (±16)
5G12P	36.2 de (±4.3)	5077 e (±576)	0.40 e (±0.06)	137 e (±1.1)	1164 ab (±16)	9.3 c (±0.57)	6.4 a (±2.59)	13.0 a (±1.2)	24.0ab (±6.1)	40.0 a (±7.6)	652 a (±75)
10G12P	31.7 cd (±6.1)	4642 de (±743)	0.28 abc (±0.05)	131 de (±2.1)	1031 ab (±13)	9.2 bc (±0.38)	8.9 b (±1.87)	13.8 ab (±1.1)	25.5abc (±9.0)	41.2ab (±6.5)	653 a (±8)
Standard	> 11.5	> 1500	> 0.35	> 50	> 600	6 ±1	≤ 8%	≤ 20	None	None	610 ±10

*: (P) Statistical significance

The SR-Y (Screw Withdrawal Strength-Surface) and the SR-K (Screw Withdrawal Strength-Edge) were found to be 39% higher in the PF sample than in UF (Tables 3 and 4). All mechanical strengths of PF were found to be higher than UF in terms of PB production. In a similar study, Viswanathan *et al.* (1999) produced PB from coconut pulp using UF and PF glue. They reported that the mechanical strength of PBs with PF glue was higher than those with UF. In another study, where particleboard was produced from sawdust using UF and PF, the results were compared, and it was reported that the mechanical and physical properties of the boards with PF were better (Mamza *et al.* 2014).

Foamed UF with 5% GL had the highest mechanical strength. Similarly, 5% GL was also found to be increasing SR-Y (Fig. 7a) and SR-K strength (Fig. 7b). Overall, 5% foaming agent provided better results than 10%. In this case, it can be said that the use of 5% and below GL can reduce glue consumption in PB.

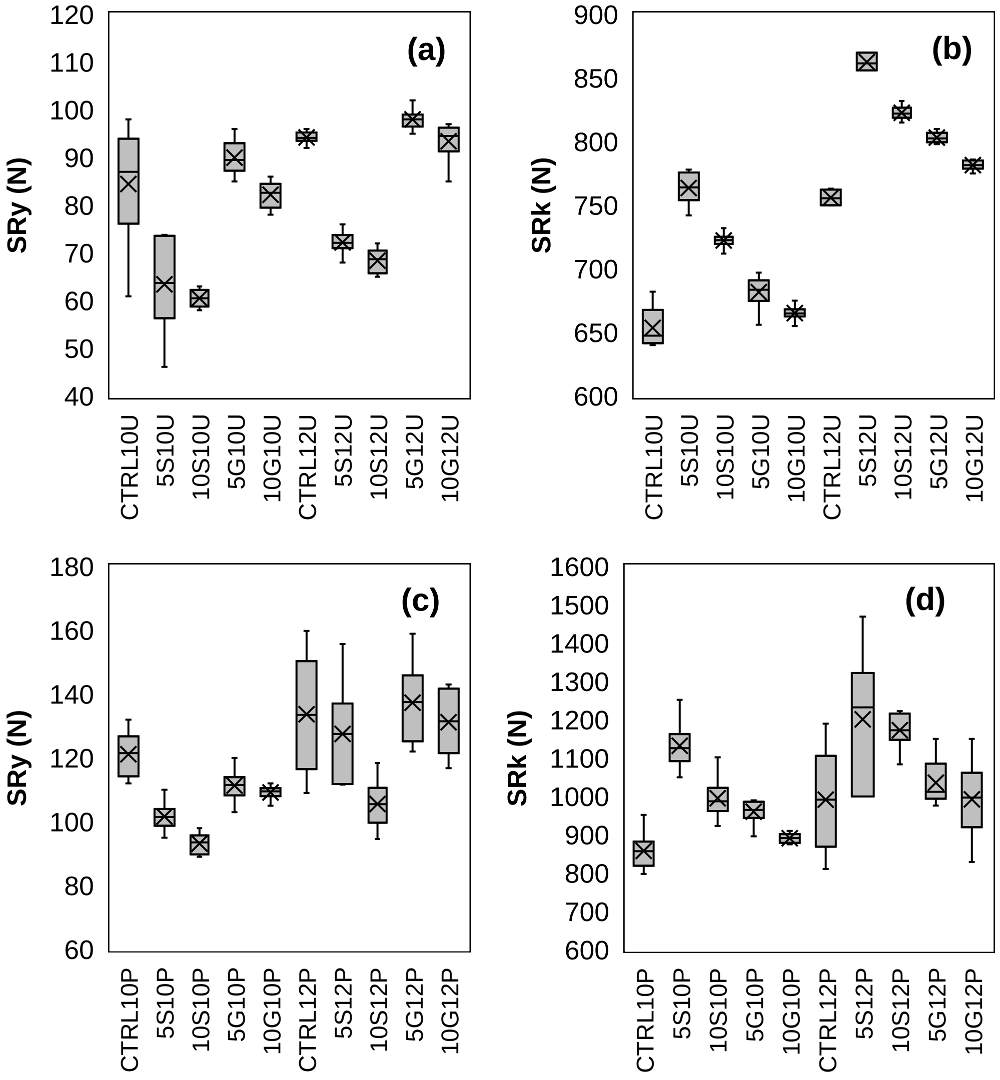

Fig. 7. UF samples surface (a) and edge (b); and PF samples surface (c) and edge (d) screw withdrawal resistance

The IB strength was low in the 5S10P sample, whereas the MOR and MOE values were high. Conversely, the IB was high, whereas MOR and MOE were low in the 10S10P sample (Figs. 8a, 8b, 8c). In fact, while surface densities increase, the MOR and MOE strengths also increased. However here, although the increasing of SB proportion caused a rise in surface densities, it caused a decrease in the MOR and MOE strengths. This may have been caused by the excessive use of SB, disrupting the adhesive mechanism. As the PB core densities increase, the IB strength is expected to increase. This increase can be observed in Fig. 8c. Foaming process with 10% SB significantly reduced the MOR and MOE strengths, while 5% SB increased the strengths of MOR and MOE. Thus, it can be said that using more than 5% SB adversely affected the mechanical strengths of the PBs. This effect can be explained by the higher WA capacities of samples foamed with SB, which led to increased WA and TS compared to other samples. Similarly, 5% GL increased IB strength, while 10% GL decreased IB strength. In this case, it is recommended not to exceed 5% SB and 5% GL in foaming PF glue. When Figs. 7c, 7d were examined, it was observed that SR-Y and SR-K were high at the points where the IB value was high. Screw withdrawal strength varies according to the type of glue, board density, and chip size used in wood composites (Joscak *et al.* 2014).

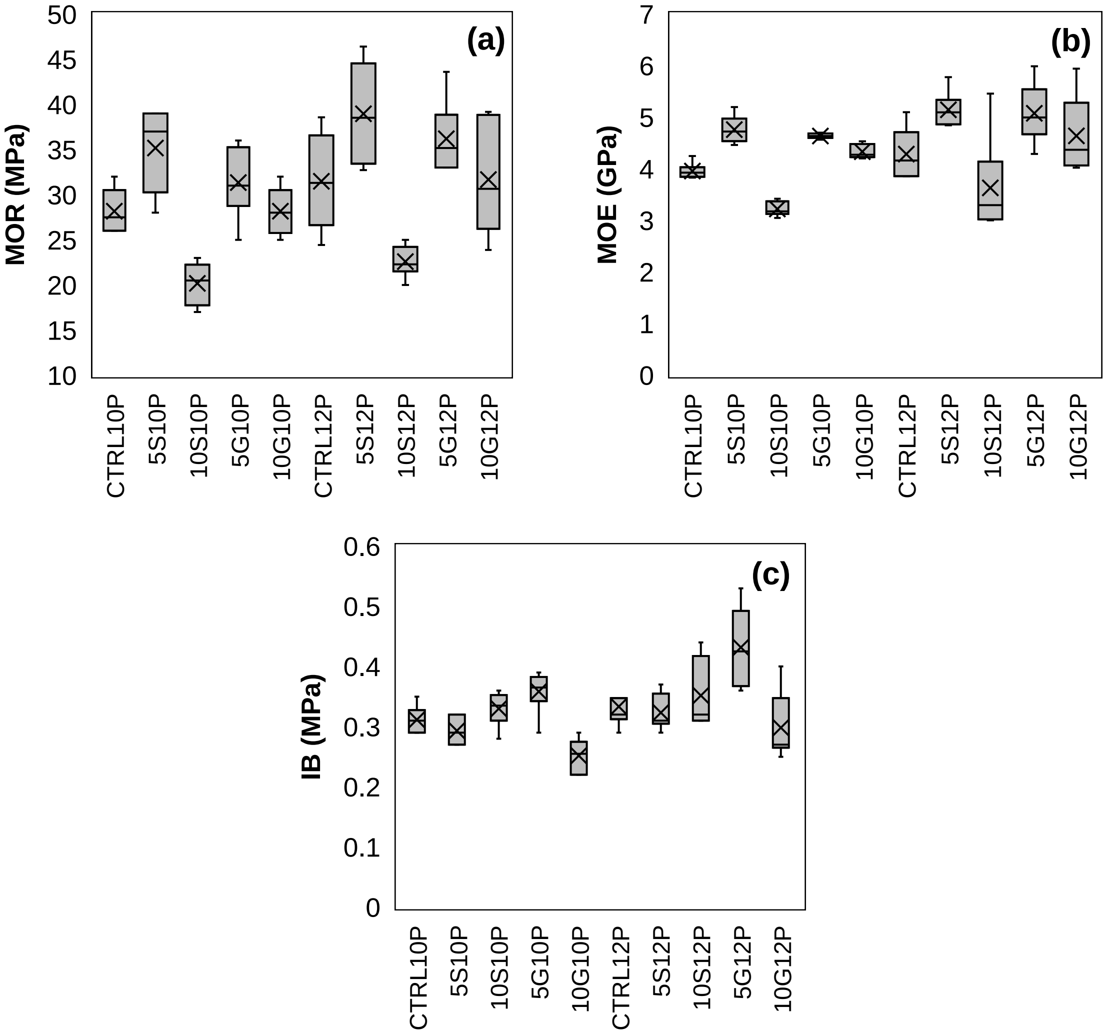

Fig. 8. Mechanical properties of samples produced with foamed PF, (a) MOR, (b) MOE and (d) IB strength

Morphological Characterization of the Foamed Resins

Figure 9 shows SEM images of neat and foamed UF and PF glues. When Fig. 9a is examined, bubble formation is observed just on the surface of neat PF (Fig. 9a). No density-reducing foam formation was detected in the inner parts of the matrix. In foaming with GL, micro and macro foam formations were detected both inside and, on the surface (Fig. 9b). The matrix had a stronger structure when foamed with GL. While micro foams were not encountered in foaming with SB, it was determined that macro-sized voids were formed in the matrix (Fig. 9c). SB also made the matrix more brittle. Additionally, SB caused a decrease in the MOR strengths of the samples but increased the WA values of foamed PF and UF.

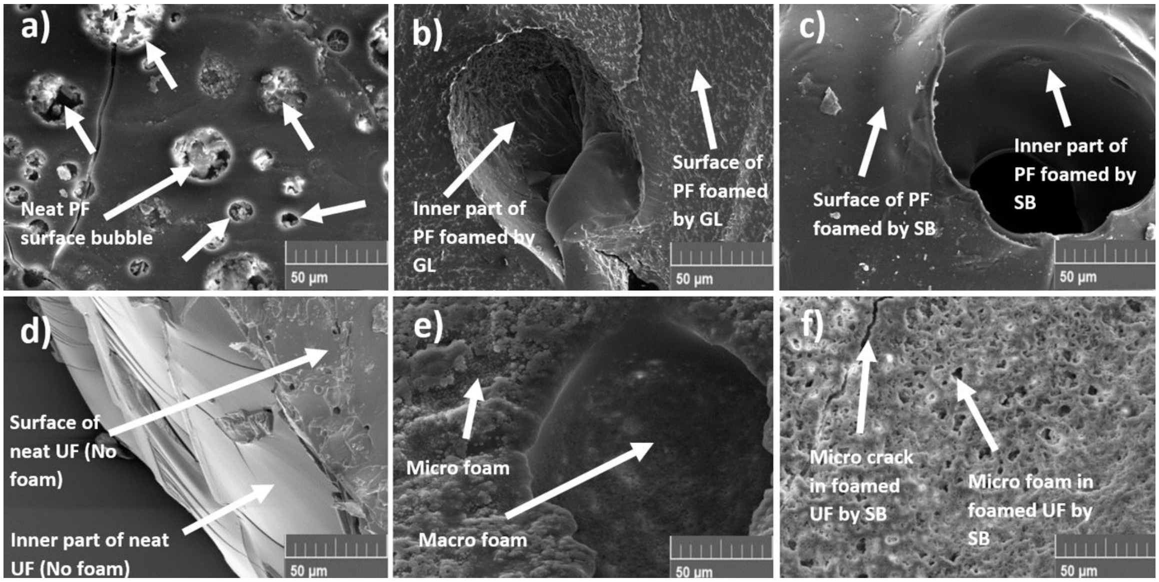

Fig. 9. SEM images of neat PF (a), foamed PF by GL (b), foamed PF by SB (c), neat UF (d), foamed UF by GL (e), and foamed UF by SB (f)

When the SEM image of neat UF was examined, no foam formation was detected in the interior and on the surface (Fig. 9d). GL gave more successful results in foaming UF. GL not only made the matrix more solid but also caused foaming in the interior and surfaces of the matrix (Fig. 9e). During foaming with SB, macro-sized foam formations were detected on the surface and inner parts of the UF (Fig. 9f). Although SB PF did not cause foaming in the matrix, UF did, so it can be said that UF is easier to foam than PF. Additionally, according to SEM images, it can be said that GL was more successful in foaming than SB. The difference between SB and GL was especially evident in the SRy and SRk values. The screw retention resistances of the GL samples were higher than those of the SB samples. It should also be noted that when the GL and SB amounts increased from 5% to 10%, the screw retention resistance decreased. When the effect of the voids formed by foaming on MOR and IB strength is evaluated, it can be said that foaming was most effective especially in the voids formed with 5% GL.

In industrial-scale PB production, a mechanical foaming machine will be needed. This machine can be mounted between the glue pump and the blender in the process (Fig. 10). In this way, the glue dosed according to the unit chip quantity is foamed and sent to the blender. The volume increase in foaming can be adjusted in laboratory tests by foaming agent concentration and machine rpm control.

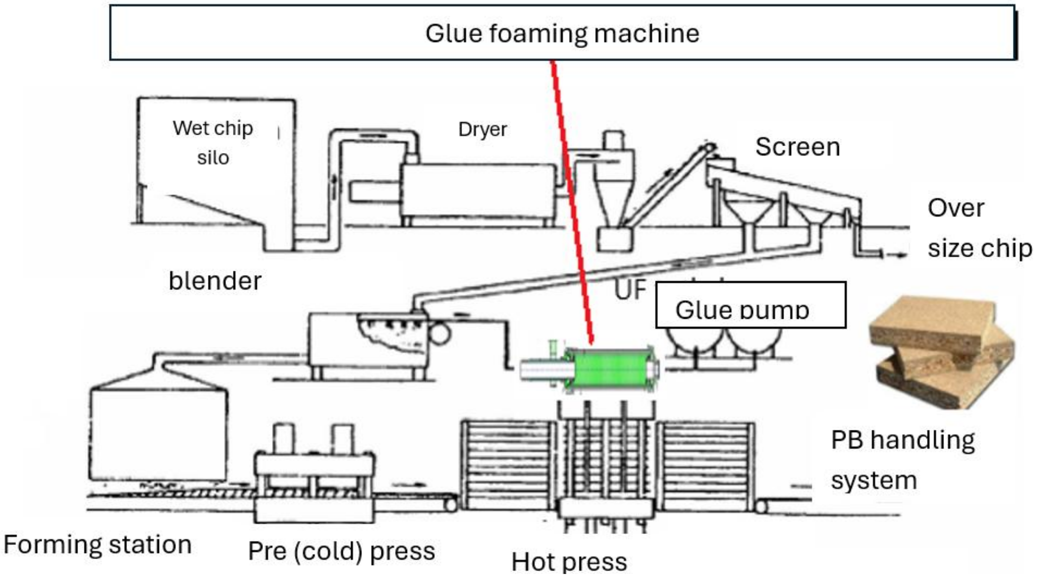

Fig. 10. Glue foaming machine installation draft in industrial process

In industrial foaming, intentional foam creation enhances process performance, while unwanted foam arises as a side effect of operations like stirring. For example, pre-foaming adhesives improve efficiency with less glue usage (Laukkanen 2019). In this study, the aim was to reduce glue usage by foaming UF and PF glues. Especially in plywood production, the air pressure method is used to ensure continuous foaming of the glue. The stability of the foam is important for efficient foaming of the glue. To ensure good adhesion between wood and glue, the foam must be of appropriate size, uniform, and strong. Mixing and foaming are done using compressed air until it foams to approximately one-fifth of its original specific gravity (Sellers Jr 1988). Proteins (*e.g.,* animal blood or soy protein) are often used as foaming agents, especially in the foaming of glue in plywood production (Hojilla-Evangelista *et al.* 2001).

Formaldehyde Content

When the formaldehyde contents of the samples produced with glue foamed with SB and GL were examined, it was determined that PF glue generally had less formaldehyde content than UF glue (Fig. 11). It was found that when UF glue was foamed with GL, the formaldehyde content of PB was 34% less than the control sample. The formaldehyde content in UF glue decreased by 17%, when UF was foamed with SB. In this case, it can be said that GL reduces the formaldehyde content effectively. Formaldehyde has the ability to interact with various functional groups present in proteins. When the spatial arrangement of these groups is favorable, formaldehyde can react with two of these groups simultaneously, creating a methylene bridge that links them together (French *et al.* 1945). Thus, formaldehyde releasing could be decreased from the PB because of the bonding of formaldehyde to GL protein.

GL was effective in foaming UF. Similar results were obtained from foamed PF. The formaldehyde content of PF with GL decreased by 30% compared to the control sample. SB, on the other hand, reduced the formaldehyde content of PF by 11%. The decrease in PB moisture also affected formaldehyde measurements. GL and SB samples decreased PB moisture. This may have caused a decrease in the amount of formaldehyde. In this case, it can be said that GL gives more effective results in foaming both UF and PF glues. When Table 5 is examined, it is seen that the significance value is lower than 0.05 (P<0.05).

Table 5. One-Way Anova Statistical Analysis Result Formaldehyde Content

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1158448.5	5	231689.7	5.219	.009
Within Groups	532758.0	12	44396.5		
Total	1691206.5	17			

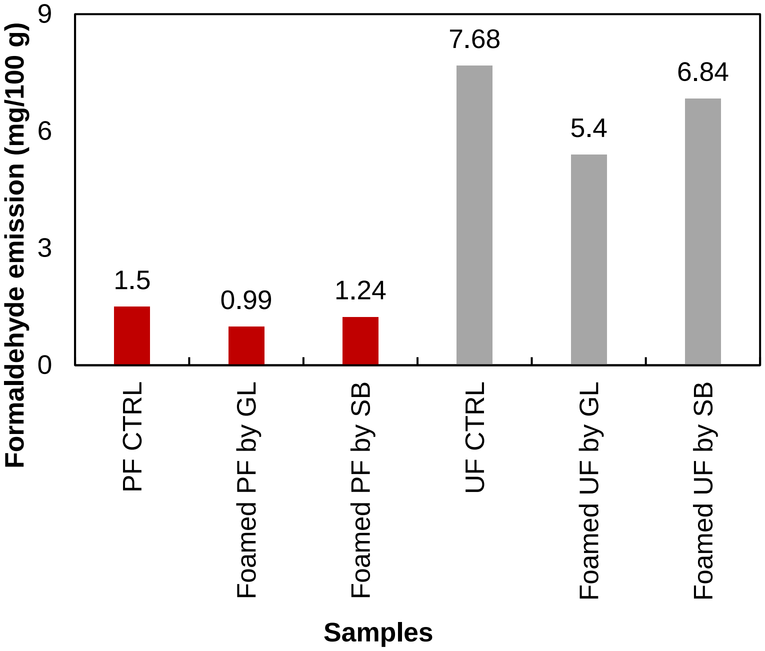

Fig. 11. Foamed and un-foamed PBs' formaldehyde content (mg/100 g in oven dry board)

Reducing formaldehyde content in particleboards is an important issue, with various restrictions in Europe. Many studies have been conducted within this context to reduce the formaldehyde emission levels of boards. Kelleci *et al.* (2022) foamed UF glue using egg white to reduce formaldehyde emission in particleboard and obtained positive results. Schopper *et al.* (2009) reduced board density by using hemp, and thus attempted to reduce formaldehyde content by using natural binder systems such as proteins and starches. In a study conducted by Puttasukkha *et al.* (2015), different amounts of scavenger were used to reduce formaldehyde emission, and it was reported that particleboard up to 12% was not negatively affected, and formaldehyde emission was reduced. Ghani *et al.* (2018) used amines to reduce the formaldehyde emission of particleboard and reported decreased emission levels, but the physical and mechanical properties of the board were negatively affected. In this study, although formaldehyde content decreased, no significant decrease in physical and mechanical properties was observed. In fact, the addition of 5% foaming agent improved the mechanical properties.

CONCLUSIONS

In this study, a different gluing method was developed for the production of particle board (PB). Urea-formaldehyde (UF) and phenol-formaldehyde (PF) glues were foamed, which increased their volume. The foaming process was carried out mechanically in a container, using sodium bicarbonate (SB) and gelatin (GL) as natural foaming agents. This method aimed to produce PB with low formaldehyde content and reduced glue consumption.

1. The PB was characterized in terms of mechanical, physical, morphological and formaldehyde content properties. According to the obtained results, PBs produced with foamed PF were found to be superior to those produced with foamed UF, in terms of physical and mechanical properties.
2. The foaming process resulted in similar graphical shapes in terms of physical and mechanical properties for both PF and UF. The IB, SR-Y, and SR-K strength of the PBs were highest with only 5% GL compared to the control samples. However, increasing the amount of GL (from 5% to 10%) reduced the mechanical strengths compared to the control sample. Similarly, increasing the amount of SB (from 5% to 10%) increased the IB strength but decreased the MOR and MOE strength. Although 5% SB and 5% GL reduced the densities, 10% SB and 10% GL increased them. Thickness swelling and water absorption were best in foamed UF and PF with 5% GL. This was caused by the fact that the use of GL increased PB moisture content, while the use of SB decreased it.
3. GL reduced formaldehyde emissions by 34% in UF resin and 30% in PF resin. SB reduced formaldehyde emissions by 17% in UF resin and 11% in PF resin. As a result, SB and GL reduced formaldehyde emissions. It can be said that GL was more successful in reducing emissions.

ACRONYMS

UF: Urea formaldehyde, **PF:** Phenol formaldehyde, **PB:** Particleboard, **GL:** Cattle gelatin, **SB:** Sodium bicarbonate, **AS:** Ammonium sulfate, **CTRL10U:** 10% Urea formaldehyde, **CTRL12U:** 12% Urea formaldehyde, **CTRL10P:** 10% Phenol formaldehyde, **CTRL12P:** 12% Phenol formaldehyde, **5S10U:** 5% Sodium bicarbonate+10% Urea formaldehyde, **10S10U:** 10% Sodium bicarbonate+10% Urea formaldehyde, **5G10U:** 5% Gelatin+10% Urea formaldehyde, **10G10U:** 10% Gelatin+10% Urea formaldehyde, **5S12U:** 5% Sodium bicarbonate+12% Urea formaldehyde, **10S12U:** 10% Sodium bicarbonate+12% Urea formaldehyde, **5G12U:** 5% Gelatin+12% Urea formaldehyde, **10G12U:** 10% Gelatin+ 12% Urea formaldehyde, **5S10P:** 5% Sodium bicarbonate+10% Phenol formaldehyde, **10S10P:** 10% Sodium bicarbonate+10% Phenol formaldehyde, **5G10P:** 5% Gelatin+10% Phenol formaldehyde, **10G10P:** 10% Gelatin+10% Phenol formaldehyde, **5S12P:** 5% Sodium bicarbonate+12% Phenol formaldehyde, **10S12P:** 10% Sodium bicarbonate+12% Phenol formaldehyde, **5G12P:** 5% Gelatin+12% Phenol formaldehyde, **10G12P:** 10% Gelatin+12% Phenol formaldehyde, **TS:** Thickness swelling, **WA:** Water absorption, **MC:** Moisture content, **MOE:** Modulus of elasticity, **MOR:** Modulus of rupture, **IB:** Internal bond strength, **SR:** Screw resistance, **SR-Y:** Screw Withdrawal Strength-Surface, **SR-K:** Screw Withdrawal Strength-Edge, **DN:** Average density

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Article submitted: December 5, 2024; Peer review completed: February 1, 2025; Revised version received: February 12, 2025; Accepted: February 13, 2025; Published: February 19, 2025.
DOI: 10.15376/biores.20.2.2765-2790