

Performance Properties of Particleboard Panels Modified with Nanocellulose/Boric Acid

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The physical and mechanical properties of particleboard panels were evaluated relative to various loading levels of nanocellulose (NC) and boric acid (BA) in the urea-formaldehyde (UF) resin used for panel production. The results showed that NC and BA reinforcement substantially affected the performance properties of the particleboard panels. It was determined that using 3% NC and 3% BA in the panels afforded the best results relative to thickness swelling (TS), water absorption (WA), moisture content (MC), modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding strength (IB). It was concluded that the performance properties of the particleboard panels could be enhanced by adjusting the loading levels of NC and BA. The study also showed that it is possible to apply NC and BA as modifiers for the formaldehyde resin in the process of manufacturing particleboard panels. The NC and BA reinforcement techniques could be used to develop novel furniture components and interior design materials.

Keywords: Boric acid; Mechanical properties; Nanocellulose; Particleboard; Physical properties; Urea-formaldehyde resin

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INTRODUCTION

In recent years, the use of lignocellulosic composites has grown because of its wide range of applications. The expanding use of lignocellulosic composites has been encouraged by a variety of factors, including the need for low-cost and high-performance composites, and the desire for sustainable industrial growth (Chen *et al.* 2020; Yildirim *et al.* 2020).

Particleboard, medium-density fiberboard (MDF), plywood, oriented strand board (OSB), laminated veneer lumber (LVL), *etc.*, are some examples of the most common types of lignocellulosic composites. Among the various types of lignocellulosic composites, the particleboard panel is a main raw material used in furniture production. Particleboard is the biggest part of the market for lignocellulosic composites (Akbulut and Ayrimis 2019). A particleboard panel is a wood-based composite consisting of lignocellulosic units of various sizes that are bonded together with a synthetic resin or binder under heat and pressure (Owodunni *et al.* 2020). It is commonly used to produce furniture, cabinets, shelving, countertops, and residential kitchens. It is also used for interior design and architectural applications.

The international market demand for particleboard is increasing day by day. Turkey is now the third-largest producer of particleboard in Europe after Russia and Germany, and it is ranked number four in the world after China, Russia, and Germany. Over the past 14 years, Turkey's lignocellulosic composites industry has achieved a remarkable average annual growth rate of about 10%, which is almost twice the global average annual growth

rate of 5.5% over the same time. As a result of high technology investments and high product quality achievements in the last 15 years, Turkey is now a net exporter of particleboard (Turkish Wood Based Panels Association 2019).

The lignocellulosic composite panel industry is a major consumer of amino resins such as urea-formaldehyde (UF) resin, phenol-formaldehyde (PF) resin, and melamine-urea-formaldehyde (MUF) resin due to its cost efficiency and proven performance in the final products (Dunky 2004). UF resin is the most widely used and important type of amino plastic adhesive for the production of lignocellulosic composites due to its high reactivity, low cost, and easy processing (Pizzi 1994; Dunky 2003; Pizzi and Mittal 2003; Mantanis *et al.* 2017). However, UF resin has the main disadvantages of poor water resistance, easy aging, and brittleness (Pizzi 1994; Dunky 1998; Gao *et al.* 2020; Liu *et al.* 2020).

Many scientists have identified nanotechnology as the revolutionary technology of the 21st century. Nanotechnology is enjoying impressive growth. The global market of nanotechnology is expected to exceed the US\$ 125 billion mark by 2024 (Liu and Xia 2020). Nanotechnology is defined as the understanding and control of matter at the nanoscale, at dimensions between 1 and 100 nanometers (Hulla *et al.* 2015). Nanotechnology offers many advantages for the forest products industry (Candan 2012; Candan and Akbulut 2013; Candan and Akbulut 2015). Studies on nanotechnology in the field of forest products are usually focused on the production of nanocellulose (NC) from wood-based lignocellulosic materials. Cellulose, the most ubiquitous and abundant natural biopolymer, has been subjected to intense research and development (Dufresne 2020; Tao and Xiu 2020). Nanocellulose consists of nanoscale cellulose-based materials derived from trees, annual plants, and agricultural residues generated by bacteria (Eskilson *et al.* 2020). The nanocellulose has unique properties including high-specific surface area, low thermal expansion coefficient, and outstanding reinforcing potential. Among many other sustainable nanomaterials, nanocellulose is drawing increasing interest for use in environmental applications due to its attractive properties.

Nanocellulose can be mainly classified into three main types; nanocrystalline cellulose (NCC), nanofibrillated cellulose (NFC), and bacterial nanocellulose (BNC). (Poyraz *et al.* 2017, 2018; Hochmanska and Janiszewska 2019). Especially, NFC particles are typically longer, more flexible, and are often branched, while NCC particles usually have short, rod-shaped particles. NFC is often used for reinforcing applications, while NCC is typically used for transparent applications. The benefits of using NC as reinforcements in adhesives for the manufacture of wood-based composite panels include the possibility of changing the properties of urea-formaldehyde, phenol-formaldehyde, and melamine-UF-based adhesives, for the improvement in physical and mechanical properties of panels (Tozluoglu *et al.* 2018; Vineeth *et al.* 2019).

Many authors have evaluated the effects of NC-modified thermosetting adhesives on the performance properties of wood-based composite panels. Zhang *et al.* (2011) used UF resins reinforced with NC for producing plywood panels. It was stated that the internal bonding strength of the plywood panels increased as NC content increased up to 1.0%. Urea-formaldehyde and melamine-UF were modified with NC and were used in particleboard and OSB production by Veigel *et al.* (2012). It was stated that thickness swelling values of the particleboard panels bonded with UF adhesive containing 1% nanocellulose were lower than the panels bonded with unreinforced-UF adhesive. Kojima *et al.* (2013) investigated the binding effect of cellulose nanofibers in wood flour board as a reinforcement. The physical and mechanical properties of wood flour boards could be improved with the addition of NC due to the better binding effect between the NC and

wood flour particles. Candan and Akbulut (2014) used melamine-UF, where resins were reinforced with various nanomaterials for producing plywood panels. It was stated that it is possible to produce novel wood composites with improved performance properties using nanotechnology. Candan and Akbulut (2015) used UF resins reinforced with various nanoparticles for producing particleboard panels. It was stated that the mechanical performance of the particleboard panels was notably increased while the physical properties of the panel were negatively affected. Cui *et al.* (2015) studied the performance enhancement of the particleboard panels with cellulose nanofibers. Thickness swelling of the particleboard panels was not affected. Internal bonding strength increased with the addition of 2% of cellulose nanofibers. The modulus of elasticity (MOE) and modulus of rupture (MOR) of the panels were particularly increased. Mahrtdt *et al.* (2016) investigated the effects of microfibrillated cellulose (MFC) addition on the distribution of urea-formaldehyde (UF) adhesive in particleboard. The authors declared that the addition of MFC to UF resin improves the mechanical bond strength of particleboard. Amini *et al.* (2017) studied the binder in the formulation of the particleboard panels with cellulose nanofibers. Physical properties, such as water absorption, thickness swelling, and mechanical properties, such as MOR, MOE, and internal bonding strength, were tested. The authors declared that particleboard panels met the industry requirements in terms of mechanical properties. Hansted *et al.* (2019) studied the physical properties of medium-density particleboard (MDP) panels after adding various proportions of nanocellulose to the UF-adhesive in MDP panel production. The authors declared that the addition of NC presented promising results from physical tests.

Boron is one of the most important industrial elements. As of 2019, Turkey had the largest reserves of boron globally. Turkey has an estimated 1.1 billion metric tons of boron in reserves (Eti Maden 2019). Boric acid is one of the most widely used boron compounds. Boron compounds have many advantages, such as retarding flame spread, low toxicity, low cost, high transparency, non-corrosiveness, and high thermal and biological resistance (Kartal 2009; Chai *et al.* 2012; Ayrimis 2013; Wu and Xu 2014; Cavdar *et al.* 2015; Li *et al.* 2020). Terzi *et al.* (2017) declared that boron compounds available in various forms are likely to continue to be among the most encouraging biocides for wood protection for future manufacturers.

The aim of this study is to investigate the effects of NC and BA mixtures in addition to UF-resin on the physical and mechanical properties of particleboard panels.

EXPERIMENTAL

A mixture consisting of 45% softwood (pine – *Pinus* spp.) and 55% hardwood (oak – *Quercus* spp. and poplar – *Populus* spp.), UF resin with solid content of 50 wt%, and liquid ammonium sulfate with solid content of 20 wt% were supplied by Kastamonu Integrated Wood Industry and Trade Inc., Istanbul, Turkey. Nanocellulose was string-like particles about 20 nm in diameter and 1 micron long. Nanocellulose used in this study was acquired from bleached wood pulp using the oxidation mediator 2,2,6,6-tetramethyl-1-piperidine-1-oxyl (TEMPO method). The other material used was boric acid (H_3BO_3). Its IUPAC name is trihydroxidoboron. The experiment was conducted with seven different reinforced levels of NC/BA loadings, as shown in Table 1.

Manufacturing of Lignocellulosic Composites

In this study, particleboard panels were manufactured as lignocellulosic composite materials. A resin reinforcement procedure was carried out in the Nanotechnology Laboratory at Istanbul University-Cerrahpasa (Istanbul, Turkey). Urea-formaldehyde resin was reinforced with NC at loading levels of 0%, 1%, 3%, and BA at loading levels of 0%, 1%, 3%, and 5%. Liquid ammonium sulfate with solid content of 20 wt% was added to the UF resin as a catalyst. Then, the UF resin was applied to the wood particles *via* a nozzle spray gun. Following the pre-pressing, the mats were put in the hydraulic hot press (Cemil Usta Company, Model: SSP 180, Istanbul Turkey). Experimental particleboard panels were pressed at 2.5 N/mm² pressure and 185 °C for 5 min. After the hot-pressing process, panels were conditioned in standard climate at 20 °C ± 2 °C and 65% ± 5% relative humidity to reach an equilibrium moisture content of approximately 12%. The edges of the particleboard panels were trimmed to a final dimension of 500 mm × 500 mm × 10 mm. For the physical and mechanical tests, three panels were produced from each particleboard type.

Table 1. Experimental Design of the Particleboard Panels

Sample ID	Nanocellulose Loading Level (%)	Boric Acid Loading Level (%)
1	0	0
2	1	1
3	1	3
4	1	5
5	3	1
6	3	3
7	3	5

Characterization of the Lignocellulosic Composites

Physical properties of the particleboard panels

The density of the particleboard specimens was determined in accordance with EN 323 (1993). Then, 24-h thickness swelling (TS) of the particleboard specimens was determined in accordance with EN 317 (1993). The changes in the dimensional stability were measured following EN 318 (1993). Moisture content (MC) of the specimens was determined in accordance with EN 322 (1993). The initial weight and thickness of all test samples were measured. Specimens were immersed vertically in a water bath at 20 ± 1 °C. The TS and water absorption (WA) values were recorded after 2 h and 24 h of water immersion periods. The TS and WA values were calculated from the weight and thickness difference in relation to initial weight and thickness of each specimen.

Mechanical properties of the particleboard panels

Mechanical characterizations for the particleboard samples were carried out at the testing machine (IB600, IMAL, Modena, Italy) of Starwood Forest Products Inc., Bursa, Turkey. The modulus of rupture (MOR) and modulus of elasticity (MOE) of the 15 particleboard specimens was determined in accordance with the requirements of EN 310 (1993). Internal bonding (IB) strengths of the 10 particleboard specimens were determined for the 15 specimens in accordance with the requirements of EN 319 (1993).

Statistical Analysis

In this work, the software (IBM SPSS Statistics 25, New York, NY, USA) was used for statistical analysis. The data obtained were evaluated by analysis of variance (two-way ANOVA) at $p < 0.05$. Significant differences between the mean values of reinforced and unreinforced groups were determined using Duncan's multiple range test.

RESULTS AND DISCUSSION

Physical Properties of the Particleboard Panels

Table 2 shows the density, TS, WA, and MC properties of particleboard panels.

Table 2. Average Physical Properties Values of Nanocellulose/Boric Acid Reinforced Particleboard Panels

Sample ID	Density (kg/m ³)	Thickness Swelling (%)		Water Absorption (%)		Moisture Content (%)	
		2 h	24 h	2 h	24 h	2 h	24 h
1	590	29.15 (3.75)	33.37 (4.20)	101.95 (16.70)	110.82 (16.49)	139.58 (30.89)	148.63 (31.00)
2	520	22.28 (3.24)	24.55 (3.44)	149.40 (9.28)	158.44 (9.17)	211.86 (19.78)	221.02 (20.20)
3	540	14.17 (2.41)	14.32 (1.82)	127.63 (9.87)	138.77 (9.12)	162.80 (12.44)	175.09 (11.81)
4	610	22.32 (6.73)	23.98 (6.08)	106.36 (10.67)	116.51 (13.60)	160.25 (9.85)	164.81 (14.21)
5	540	19.87 (4.19)	22.20 (4.18)	131.64 (10.55)	135.11 (10.06)	176.21 (15.46)	188.62 (14.99)
6	580	16.83 (1.90)	19.53 (2.09)	108.57 (34.53)	118.62 (35.98)	137.11 (18.64)	148.52 (18.20)
7	550	17.50 (1.63)	20.01 (1.79)	125.24 (4.68)	131.79 (4.80)	152.94 (5.57)	163.33 (5.60)

Standard deviation values are shown in parentheses

Density

The density dispersion within lignocellulosic composites is one of the most significant panels quality properties which largely determines panel end uses. The average density values of the NC and BA reinforced particleboard panels ranged between 520 and 610 kg/m³. The panel groups exhibited similar density values.

Thickness Swelling

The average TS values of NC/BA reinforced particleboard panels after 2 and 24 h water soaking periods are given in Table 2. The results showed that the TS values of the NC and BA modified particleboard panels were significantly lower than those of unreinforced panels during 2 and 24 h water soaking periods. TS values after all water soaking periods of the particleboard panels decreased with increasing NC loading level, except the composites reinforced with 3% NC/3% BA. The 1% NC/3% BA and 3% NC/3% BA reinforced panels had a maximum decrease in 24 h TS values with 57.0% and 41.4%, compared with unmodified panels.

A material can take on water without its thickness necessarily increasing. Since the holding of wood particles between each other increases, the thickness swelling decreases relatively. There may be decreases or no expected increases in some groups due to certain rates or unexpected reasons, such as aggregation.

Two-way ANOVA was performed to evaluate the influence of the NC and BA loading levels and the combined effect of the factors on TS properties of the particleboard panels after 24 h.

The results indicated that the F-value for nanocellulose ratio was 19.105. Thus, there was a significant difference in thickness swelling quantity between panel groups at a 95% confidence level due to the value of 19.105 is greater than the value received from the related statistical tables. The F-value for the boric acid ratio was found to be 33.570. There was a significant difference in thickness swelling quantity between panel groups at a 95% confidence due to the value of 33.570 was greater than the value received from the related statistical tables. The F-value for NC/BA ratio was found to be 18.178. There was a significant difference in thickness swelling quantity between panel groups at a 95% confidence level due to the value of 18.178 is greater than the value received from the related statistical tables.

According to the results of Duncan's test conducted to investigate the effect of NC ratio on the TS values of particleboards, a significant difference was found between the panel groups at a 95% confidence level. In this case, three homogeneous subgroups were formed. According to the results of Duncan's test conducted to investigate the effect of BA ratio on the TS values of particleboards, a significant difference was found between the panel groups at a 95% confidence level. In this case, three homogeneous subgroups were formed.

These results are supported by previous work from Hansted *et al.* (2019), who used NC, reinforced UF-adhesives during the MDP panels production. The authors reported that the addition of NC had a positive effect on thickness swelling. Sun *et al.* (2019) reported that the shows a small positive effect of CNF addition on thickness swelling.

Water Absorption

The average WA values of NC/BA reinforced particleboard panels after 2 h and 24 h water soaking periods are given in Table 2. The results revealed that WA values of the NC and BA modified particleboard panels were slightly higher than those of unreinforced particleboard panels, except that of the composites reinforced with 1% NC and 5% BA. The WA values after all water soaking periods of the particleboard panels decreased with increasing NC and BA loading levels, except the composites reinforced with 3% NC/5% BA. The highest WA values for all water soaking periods were determined in the particleboard panels reinforced with 1% NC and 1% BA.

In general, OH-groups are abundant in nanocellulose materials, making the material strongly hydrophilic. Due to the hydrophilic structure of nanocellulose/boric acid, water entered the structure, and WA values have been high compared to the unmodified group.

The addition of boric acid formed a strong interaction with nanocellulose, hence it decreased the water absorption remarkably. Boric acid could chemical that can interact with nanocellulose create cross-links within the wood particles, which results in a significant decrease in water absorption. Consequently, the water absorption of particleboard panels decreases as the increase of BA level.

Two-way ANOVA was performed to evaluate the influence of the modifier loading levels, and the combined effect of the factors on water absorption properties of the particleboard panels after 24 h.

The results indicated that the F-value for nanocellulose ratio was 21.933. There was a significant difference in WA between panel groups at a 95% confidence level due to the value of 21.933 being greater than the value received from the related statistical tables. The F-value for the boric acid ratio was 30.294. There was a significant difference WA between panel groups at a 95% confidence level due to the value of 30.294 was greater than the value received from the related statistical tables. The F-value for NC/BA ratio was found to be 6.275. There was a significant difference in WA between panel groups at a 95% confidence level due to the value of 6.275 being greater than the value received from the related statistical tables.

According to the results of Duncan's test conducted to investigate the effect of NC ratio on the WA values of particleboards, no significant difference between the control group panels (NC rate = 0%) and the panel groups produced using 1% NC, at 95% confidence level. There was a significant difference between the other panel groups. In this case, two homogeneous subgroups were formed. According to the results of Duncan's test conducted to investigate the effect of BA ratio on the WA values of particleboards, no significant difference between the control group panels (BA rate = 0%) and the panel groups produced using 3% boric acid, at 95% confidence level. There was a significant difference between the other panel groups. In this case, three homogeneous subgroups were formed.

These results are supported by previous studies of Kartal *et al.* (2007), who evaluated the water absorption of wood specimens treated with boron compounds. The authors reported that the modified wood caused increased water absorption due to the hygroscopicity of boric acid. Pawlak and Boruszewski (2018), who used micro-fibrillated cellulose, reinforced UF-adhesives during the low-density particleboard production. The authors reported that the addition of micro-fibrillated cellulose had a positive effect on the water resistance.

Moisture Content

The average MC values of NC/BA reinforced particleboard panels after 2 and 24 h water soaking periods are given in Table 2. The findings indicated that the NC/BA reinforced particleboard panels had significantly higher MC values than those of unreinforced panels. The MC values after all water soaking periods of the particleboard panels decreased with increasing NC and BA loading levels, except for the composites reinforced with 3% NC/5% BA. It was determined that using 3% NC and 3% BA in the particleboard panels resulted in the lowest MC values. The higher moisture content of panels with higher levels of NC can be attributed to the loss of bonds between the wood particles during water soaking.

Two-way ANOVA indicated that the NC and BA loading levels and their combined factors significantly affected the MC values of the particleboard panels after 24 h water soaking periods.

The results indicated that the F-value for nanocellulose ratio was 6.797. There was a significant difference in moisture content quantity between panel groups at a 95% confidence level due to the value of 6.797 was greater than the value received from the related statistical tables. The F-value for the boric acid ratio was 50.705. There was a significant difference in moisture content quantity between panel groups at a 95%

confidence level due to the value of 50.705 is greater than the value received from the related statistical tables. The F-value for NC/BA ratio was 10.059. There was a significant difference in moisture content quantity between panel groups at a 95% confidence level due to the value of 10.059 was greater than the value received from the related statistical tables.

According to the results of Duncan's test conducted to investigate the effect of NC ratio on the MC values of particleboards, no significant difference was found between the panel groups at a 95% confidence level. In this case, one homogeneous subgroup was formed. According to the results of Duncan's test conducted to investigate the effect of BA ratio on the MC values of particleboards, a significant difference was found between the panel groups at a 95% confidence level. In this case, two homogeneous subgroups were formed.

Gabr *et al.* (2013) reported that nanocellulose had a negative effect on moisture absorption. Hansted *et al.* (2019) reported that the addition of NC resulted in no significant statistical difference in the density and MC of the MDP panels.

Mechanical Properties of the Particleboard Panels

Table 3 shows the average values of the MOR, MOE, and IB strengths.

Table 3. Average Mechanical Properties Values of Nanocellulose/Boric Acid Reinforced Particleboard Panels

Sample ID	Modulus of Rupture (N/mm ²)	Modulus of Elasticity (N/mm ²)	Internal Bonding (N/mm ²)
1	2.95 (0.37)	516.52 (87.77)	0.19 (0.05)
2	2.30 (0.72)	322.68 (110.52)	0.14 (0.03)
3	3.05 (0.75)	565.92 (101.82)	0.25 (0.06)
4	2.92 (0.47)	526.92 (104.64)	0.13 (0.05)
5	2.72 (0.98)	400.98 (135.16)	0.18 (0.03)
6	4.43 (0.69)	666.88 (61.73)	0.39 (0.10)
7	3.70 (0.56)	544.92 (73.26)	0.31 (0.06)

Standard deviation values are shown in parentheses

Modulus of Rupture

The modulus of rupture measures the ultimate load-carrying capacity in lignocellulosic composites. The average MOR results of reinforced particleboard panels are given in Table 2. It is apparent that the NC reinforcement affected the MOR performance of the particleboard panels. While the lowest MOR value of panels which were produced at 1% NC/1% BA ratio was calculated as 2.30 N/mm², the highest value was obtained in 3% NC/3% BA, calculated as 4.43 N/mm² with an improvement of approximately 50.1%. The MOR values of the reinforced panels increased significantly with increasing the NC/BA loading levels from 1% to 3%.

Two-way ANOVA results indicated that the MOR values of the particleboard panels were significantly affected. The results indicated that the F-value for nanocellulose ratio was 12.510. There was a significant difference in MOR between panel groups at a 95% confidence level due to the value of 12.510 being greater than the value received from the related statistical tables. The F-value for the boric acid ratio was 27.037. There was a significant difference MOR between panel groups at a 95% confidence level due to the

value of 27.037 was greater than the value received from the related statistical tables. The F-value for NC/BA ratio was 3.993. There was a significant difference in MOE between panel groups at a 95% confidence level due to the value of 3.993 is greater than the value received from the related statistical tables.

According to the results of Duncan's test conducted to investigate the effect of NC ratio on the MOR values of particleboards, a significant difference was found between the panel groups at a 95% confidence level. In this case, two homogeneous subgroups were formed. According to the results of Duncan's test conducted to investigate the effect of the BA ratio on the MOR values of the particleboards, no significant difference between the control group panels (BA ratio = 0%) and the panel groups produced using 5% BA, at 95% confidence level. There was a significant difference between the other panel groups. In this case, three homogeneous subgroups were formed.

Veigel *et al.* (2012) concluded that the particleboard panels bonded with an adhesive containing 1% NC had higher MOR values than the particleboard panels with neat UF-adhesive. Rojo *et al.* (2015) indicated that the cellulose loading level significantly affected the mechanical properties of the composites. It was reported that low cellulose loading levels, such as 1%, decreased the mechanical properties of the composites. Leng *et al.* (2017) studied wet-formed particleboard bonded with cellulose nanofibrils (CNF). The authors reported that the CNF addition ratio had the most significant effect on the MOR. Claramunt *et al.* (2019) concluded that the addition of 0.1 to 0.2 wt% of either type of nanocellulose led to an increase in the MOR values. Sun *et al.* (2019) declared that the CNF impressively improved the modulus of rupture at low addition rates.

Modulus of Elasticity

The modulus of elasticity measures the resistance to bending and reveals the stiffness of the lignocellulosic composites. The average MOE results of reinforced particleboard panels are given in Table 2. The MOE values of the NC and BA reinforced particleboard panels were higher than those of the unreinforced particleboard panels, except that of the panels reinforced with 1% NC/1% BA, 3% NC/1% BA. The MOE values of the reinforced panels increased significantly with increasing the NC/BA loading levels from 1% to 3%. The highest MOE value was obtained in 3% NC and 3% BA reinforced particleboard panels with an improvement of approximately 29%.

Two-way ANOVA indicated that the NC and BA loading levels and combined effect of the two factors significantly affected the MOE values of the particleboard panels. The F-value for nanocellulose ratio was 28.875. There was a significant difference in MOE between panel groups at a 95% confidence level due to the value of 28.875 being greater than the value received from the related statistical tables. The F-value for the boric acid ratio was 52.547. There was a significant difference in MOE between panel groups at a 95% confidence level due to the value of 52.547 was greater than the value received from the related statistical tables. The F-value for NC/BA ratio was found to be 1.399. There was no significant difference in MOE between panel groups at a 95% confidence level due to the value of 1.399 being smaller than the value received from the related statistical tables.

According to the results of Duncan's test conducted to investigate the effect of NC ratio on the MOE values of particleboards, a significant difference was found between the panel groups at 95% confidence level. In this case, two homogeneous subgroups were formed. According to the results of Duncan's test conducted to investigate the effect of BA ratio on the MOE values of particleboards, no significant difference between the control group panels (BA rate = 0%) and the panel groups produced using 5% BA, at 95%

confidence level. There was a significant difference between the other panel groups. In this case, three homogeneous subgroups were formed.

The results obtained are supported by the previous work of Nakagaito and Yano (2008), which revealed that there was no linear relationship between Young's modulus of the composites and cellulose fiber content. Cui *et al.* (2015) concluded that the particleboard panels containing CNF of the resins were also notably increased. Efhamisisi *et al.* (2016) reported the addition of BA increased the modulus of elasticity of the adhesive. Claramunt *et al.* (2019) concluded that the addition of nanocellulose significantly improving MOE values. Sun *et al.* (2019) declared that the CNF increased the modulus of elasticity, optimally at 2.5% addition. Kawalerczyk *et al.* (2020) concluded that NC had a positive effect on MOE.

Internal Bonding Strength

IB is one of the most significant tests, and it was used as a determiner of the inner bond quality of panels. The average IB results of reinforced particleboard panels are given in Table 2. It displays that the NC/BA reinforcement significantly affected the IB performance of the particleboard panels. It was found that the IB values of the panels ranged between 0.13 and 0.39 N/mm². When the nanocellulose ratio was increased from 1% to 3%, the internal bond increased from 0.13 to 0.31 N/mm². The IB values of the reinforced panels increased significantly with increasing the NC/BA loading level from 1% to 3%. The highest IB value was obtained in 3% NC and 3% BA reinforced particleboard panels, with an improvement of 100%. As can be seen from the IB results or other mechanical performance, generally nanocellulose reinforcement affected positively the final panels' performance. Nanocellulose enhances the internal bonding strength properties of the adhesive. Thanks to the high specific surface area and fiber structure on a nanoscale, nanocellulose creates strong bonds. Therefore, mechanical strength values were increasing with the addition of NC.

Two-way ANOVA showed that the NC and BA loading levels and their combined effect significantly affected the IB strength values of the particleboard panels. The results indicated that the F-value for nanocellulose ratio was 31.034. There was a significant difference in IB strength between panel groups at a 95% confidence level due to the value of 31.034 was greater than the value received from the related statistical tables. The F-value for the boric acid ratio was 73.618. There was a significant difference in IB strength between panel groups at a 95% confidence level due to the value of 73.618 was greater than the value received from the related statistical tables. The F-value for NC/BA ratio was 12.623. There was no significant difference in IB strength between panel groups at a 95% confidence level due to the value of 12.623 was smaller than the value received from the related statistical tables.

According to the results of Duncan's test conducted to investigate the effect of NC ratio on the IB strength values of particleboards, a significant difference was found between the panel groups at a 95% confidence level. In this case, three homogeneous subgroups were formed. According to the results of Duncan's test conducted to investigate the effect of BA ratio on the IB strength values of particleboards, a significant difference was found between the panel groups at a 95% confidence level. In this case, four homogeneous subgroups were formed.

These results are supported by the previous report of Zhang *et al.* (2011), who examined bonding quality properties of the UF bonded plywood panels. It was indicated that the bonding quality of the composite panels increased with nanocellulose because of

interactions between nanocellulose and UF adhesive. Parallel results were also found by Cui *et al.* (2015). They investigated the effect of CNF on the performance properties of particleboard panels. Internal bonding strength increased with the addition of 2% of NC. Efhamisi *et al.* (2016) reported the BA in the glue line improved the bonding quality of the panels. Hunt *et al.* (2017) investigated the effects of IB strength properties of NC-containing particleboards. The authors reported that the increased NC ratio could improve IB properties for the high-density particleboard. Kasmani and Samariha (2019) declared that the addition of NFC at 8% increased the tensile strength compared to 0% NFC (10.9%).

CONCLUSIONS

1. The results obtained in this study revealed that nanocellulose (NC) and boric acid (BA) reinforcement significantly affected the physical and mechanical performance properties of the particleboard panels.
2. The use of NC/BA reinforcement technique caused an increase of water absorption (WA) and moisture content (MC), while reducing the thickness swelling (TS) of the particleboard.
3. Modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding (IB) properties of particleboard panels produced with an optimum amount of NC increased greatly in comparison to the unreinforced samples. If the particleboard panels are to be used for mechanical strength applications, NC and BA loading level should not be less than 3%.
4. It was concluded that the physical and mechanical performance properties of the lignocellulosic composites could be enhanced by altering the NC and BA loading levels.

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