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Boron Compounds-Added Kraft Pulping from Scots Pine

Kraft celuloza od borovine s dodatkom spojeva bora

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ABSTRACT • *In this study, effects of KBH_4 (PB), $NaBH_4$ (SB), Etibor-48 (E48), Etidot-67 (E67), and colemanite (Col) on kraft pulp and paper properties of Scots pine (Pinus sylvestris L.) wood were evaluated. The control and boron compound-added kraft pulps were obtained under constant cooking conditions. The boron compounds were used as digester additives in different ratios (2 % and 4 %). The addition of boron compounds to kraft cooking liquor resulted in increases screened and total yield of pulps. The highest screened yield (52.05 %) and total yield (55.09 %) were obtained from PB-4 pulp. The lowest reject ratio (0.61 %) and kappa number (34.60) were determined from PB-2 pulp. Furthermore, the highest tensile properties of handsheets were obtained from E67-4 pulp. Also, E48-4 pulp had the highest burst index and tear index values. E48, E67, and Col are cheaper than PB and SB. From these boron compounds, pulps with relatively low pulp yield but stronger can be obtained.*

KEYWORDS: *Pinus sylvestris; pulp yield; boron compounds; pulp strength*

SAŽETAK • *U ovom je istraživanju proučavan utjecaj KBH_4 (PB), $NaBH_4$ (SB), Etibor-48 (E48), Etidot-67 (E67) i kolemanita (Col) na kraft celulozu i svojstva papira od borovine (Pinus sylvestris L.). Kontrolna i kraft celuloza s dodatkom spojeva bora dobivene su pri konstantnim uvjetima kuhanja. Spojevi bora upotrijebljeni su kao dodatci za poboljšanje digestije u različitim omjerima (2 i 4 %). Dodavanje spojeva bora tekućini za kuhanje rezultiralo je povećanjem prinosa nakon prosijavanja i ukupnog prinosa celuloze. Najveći prinos nakon prosijavanja (52,05 %) i najveći ukupni prinos (55,09 %) dobiveni su za celulozu PB-4. Najmanji omjer odbacivanja (0,61 %) i kappa broj (34,60) utvrđeni su za celulozu PB-2. Nadalje, najveća vlačna svojstva listova papira dobivena su za celulozu E67-4. Također, celuloza E48-4 imala je najveće vrijednosti indeksa probijanja i vlačnog indeksa. E48, E67 i kolemanit jeftiniji su od PB i SB. Od tih spojeva bora može se dobiti čvršća celuloza, ali s relativno malim prinosom celuloze.*

KLJUČNE RIJEČI: *Pinus sylvestris; prinos celuloze; spojevi bora; čvrstoća celuloze*

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1 INTRODUCTION
1. UVOD

Scots pine is a significant trading tree species that is extensively planted for conservation and industrial activities such as live snow hedges and soil erosion protection (Şevik and Topaçoğlu, 2015). Scots pine forests cover 28 million hectares in Europe (Bußkamp *et al*., 2020). Scots pine covers 1.41 million hectares of Türkiye forests and has a 6.15 % share of the Turkish forested area (OGM, 2021).

Türkiye has 73 % of the world's boron reserves based on B_2O_3 content. It is also the world's largest producer of boron compounds (57 % of the boron market). Türkiye's annual boron compound production is 1.73 million tons. The main boron minerals in Türkiye are ulexite ($NaCaB_5O_9 \cdot 8H_2O$) colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$), and tincal ($Na_2B_4O_7 \cdot 10H_2O$) (Eti Mine, 2021).

The pulp industry has commercially used chemical or mechanical pulping methods, or a combination of the two, to obtain pulps with desirable properties. Chemical pulp accounts for approximately 75 % of the world's wood pulp production. Among the chemical pulp production methods, kraft pulping is the most widely used method and the strength properties of kraft pulp are higher compared to other methods. This process produces very high-strength papers. However, the process also has some negative aspects such as giving relatively low yields, being capital and energy-intensive, producing relatively low-value by-products, and generating problematic wastes (Das and Houtman, 2004).

In 2020, the world's paper and paperboard production was 401 million metric tons. The global chemical pulp production volume in 2020 was 148 million metric tons (FAO, 2021). Due to the rapid increase in paper consumption and demand, chemical pulp mills are aiming to find new lignocellulosic raw materials for pulp production (Kaur *et al*., 2018) or to increase pulp yield with various cooking liquor additives. In the chemical pulping process, cooking chemicals (NaOH, Na_2S, etc.) combined with heat break down the lignin. During pulping, carbohydrate losses and thus the pulp yield losses also occur. The oxidation or reduction of carbohydrate reducing end can prevent these losses. For this purpose, SB was extensively studied as cooking liquor additive in the several lignocellulosic biomass such as *Pinus radiata* (Meller, 1963; Meller and Ritman, 1964), *Pinus brutia* (Akgul *et al*., 2007; Copur and Tozluoglu, 2008; Tutuş *et al*., 2012; Saraçbaşı *et al*., 2016), *Pinus pinaster* (İstek and Gonteki, 2009), *Pinus pinea* (Gümüşkaya *et al*., 2011), *Abies bornmulleriana* (Akgul and Temiz, 2006), *Picea orientalis* (Tutus *et al*., 2010a; Erişir *et al*., 2015), *Populus tremula* (İstek and Ozkan, 2008), *Diospyros kaki* (Tutuş *et al*., 2014), *Prunus armeniaca* (Tutuş *et al*., 2016), *Castanea sativa* and *Corylus colurna* (Aytekin, 2011), *Eucalyptus camaldulensis* and *Eucalyptus grandis* (Ayata, 2008), *Rhododendron luteum* and *Rhododendron ponticum* (Birinci *et al*., 2020), *Acer saccharum* (Letho *et al*., 2021), *Cyperus papyrus* (Gabir and Khristov, 1973), *Gossypium hirsutum* (Tutus *et al*., 2010b), *Brassica napus* (Akgül *et al*., 2018), poppy stems (Tutuş *et al*., 2011), and wheat straw (Tutus and Alma, 2005; Tutuş and Çiçekler, 2016). PB was also used in a few lignocellulosic biomass types such as *Pinus pinaster* (Gülsoy *et al*., 2016), *Pinus brutia* (Çiçekler and Tutuş, 2019), *Pinus pinea* (Erkan *et al*., 2020), *Robinia pseudoacacia* (Çiçekler *et al*., 2021), and *Pteridium aquilinum* (Gülsoy and Şimşir, 2018). However, the influences of E48, E67, and Col on pulp and paper properties were investigated only in *Pinus nigra* and *Populus tremula* (Kilic Pekgözlü *et al*., 2017). To the best of our knowledge, there was no published data regarding the influences of boron compounds on pulp and paper properties of Scots pine. To this scope, we evaluated the effects of SB, PB, E-48, E-67, and Col additions at the different ratios (2 % and 4 % oven-dried wood) as cooking liquor additives on pulp and paper properties of Scots pine.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Scots pine, a commercially important forest tree, was obtained from the Bartin province of Türkiye. The bark of the wood samples was peeled and crumbled in 3.5-1.5-0.5 cm dimensions to be made into pulp. The chips were air-dried to 12 % final humidity and stored in dry conditions. SB and PB were purchased from Merck. E48 ($Na_2B_4O_7 \cdot 5H_2O$), E67 ($Na_2B_8O_{13} \cdot 4H_2O$), and Col ($CaB_3O_4(OH)_3$-$H_2O$) were obtained from Eti Mine (Türkiye). The boron oxide (B_2O_3) contents of E48, E67, and Col were 48 %, 67 %, and 40 %, respectively.

Chemical analysis samples were prepared according to the TAPPI T 257 standard. The holocellulose (Wise and Karl, 1962), lignin (TAPPI T 222), α-cellulose (TAPPI T 203), cold-hot water solubility (TAPPI T 207), ethanol solubility (TAPPI T 204), and 1 % NaOH solubility (TAPPI T 212) of samples were determined according to the relevant methods. On the other hand, Scots pine samples were macerated by the chlorite method (Spearin and Isenberg, 1947). Fiber length (L), fiber width (D), lumen width (d), and cell wall thickness (w) of 100 randomly selected fibers were measured. The flexibility ratio [(d/D) × 100], slenderness ratio (L/D), and Runkel ratio (2w/d) were calculated using the measured fiber sizes.

Kraft pulping conditions were as follows: 25 % sulfidity, 18 % active alkali as Na_2O, 4:1 liquor/wood ratio, 90 min. to cooking temperature, 75 min. at cooking temperature, and 170 °C cooking temperature. The 2 % and 4 % (oven-dried wood) of each boron compound were added to kraft cooking liquor. Abbreviations of 2 % and 4 % KBH_4-added cookings were PB-2 and 4% PB-4. The cookings of other boron compounds (SB, E48, E67, and Col) were carried out with similar abbreviations. The boron compound-free (C) was also done as a control. In each cooking, 700 g of wood chips (oven-dried) were cooked in a laboratory-type rotary digester. After digestion, pulps were washed with tap water and were disintegrated in a pulp mixer. Somerville-type pulp screen (TAPPI T 275) was used in the screening of pulp samples. Pulp samples were then beaten to 25 °SR in a Valley Beater according to TAPPI T 200. Freeness, viscosity, screened yield, and kappa number of pulps were determined according to ISO 5267-1, SCAN CM 15-62, TAPPI T 210, and TAPPI T 236, respectively. 75 g/m^2 handsheets made by a Rapid-Kothen Sheet Former (ISO 5269-2) were conditioned according to TAPPI T 402. Tensile properties (tensile index, stretch, and TEA) (ISO 1924-3), tear index (TAPPI T 414), burst index (TAPPI T 403), and brightness (TAPPI T 525) of the handsheets were determined according to standard methods. The data of the handsheet properties for all pulp samples were statistically analyzed using analyses of variance (ANOVAs) and the Duncan test at a 95 % confidence level. In Figure 1-6, the different letter lowercase indicates that the difference in the mean values of properties among the compared groups was statistically significant ($P<0.05$).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The chemical composition and fiber morphology of Scots pine are given in Table 1 and Table 2, respectively. These results showed that both the chemical composition and fiber morphology of Scots pine used in this study were similar to previous studies.

The pulp yield of kraft pulping is relatively low. Therefore, some researchers have aimed to increase pulp yield using digester additives such as anthraquinone, polysulfur, $NaBH_4$. The screened yields of pulps (except for E67-4 pulp) were increased with the addition of boron compounds. The highest screened pulp yield, increasing by 13.97 % (6.38 points from 45.67 % to 52.02 %), was obtained from PB-4 pulp. E67-4 pulp (45.51 %) had a lower screened yield than the control pulp (45.67 %) (Table 3). The screened pulp yields of all boron compounds-added pulps were increased with increasing boron addition ratios (except for E67-4 pulp). However, the holocellulose contents of E67-4, Col-2, and Col-4 pulps were lower than the control pulp (Table 3). These results showed that hemicellulose retention during pulping was significantly increased with PB, SB, and E48 additions (both 2 % and 4 %) to cooking liquor. However, hemicellulose retention was slightly increased in the E67-2 pulping. The total pulp yields of all pulps were also increased with boron additions (Table 3). The highest total pulp yield, increasing by 15.43 % (8.50 points from 46.59 % to 55.09 %), was obtained from PB-4 pulp. These results can be ascribed to the preven-

Table 1 Chemical composition of Scots pine
Tablica 1. Kemijski sastav borovine

Chemical compositions, % *Kemijski sastav, %*	Present study *Ovo istraživanje*	Alkan, 2004	Dönmez, 2010	Tutuş *et al.*, 2010
Holocellulose / *holoceluloza*	66.92±1.15	70.97	65.75	73.67
α-cellulose / *α-celuloza*	43.53±0.36	-	46.27	-
Klason lignin / *Klasonov lignin*	25.02±0.16	23.57	27.23	28.57
Ethanol solubility / *ekstrakt u etanolu*	8.47±0.22	-	4.52	-
Hot water solubility / *ekstrakt u vrućoj vodi*	2.58±0.04	6.64	8.45	3.82
Cold water solubility / *ekstrakt u hladnoj vodi*	1.58±0.02	5.74	-	3.42
1 % NaOH solubility / *ekstrakt u 1 % NaOH*	10.61±0.47	13.83	10.62	16.28

Table 2 Fiber morphology of Scots pine
Tablica 2. Morfologija vlakana borovine

Fiber properties *Svojstva vlakana*	Present study *Ovo istraživanje*	Alkan, 2004	Dönmez, 2010	Gulsoy *et al.*, 2013
Fiber length mm / *duljina vlakana,* mm	2.89±0.70	4.01	3.47	3.00
Fiber width, µm / *širina vlakana,* µm	38.05±7.08	49.00	44.10	46.30
Lumen width, µm / *širina lumena,* µm	19.86±6.65	34.80	26.61	23.40
Cell wall thickness, µm / *debljina stanične stijenke,* µm	9.14±2.84	7.10	8.74	11.45
Slenderness ratio / *omjer vitkosti*	75.95	81.91	78.70	64.79
Flexibility ratio / *omjer fleksibilnosti*	52.19	71.02	60.34	50.54
Runkel ratio / *Runkelov omjer*	0.92	0.40	0.66	0.98

tion of degradation reactions by boron compounds during pulping. Kilic Pekgözlü *et al*. (2017) noted that screened pulp yield of *Populus tremula* kraft pulp was decreased with the addition of Col. The authors also reported that E48 and E67 caused screened yield increases. The positive effect of SB on pulp yield was reported in previous studies (Ayata, 2008; İstek and Gönteki, 2009; Gümüşkaya *et al*., 2011; Gulsoy and Eroglu, 2011; Tutuş *et al*., 2012; Tutuş *et al*., 2014; Erişir *et al*., 2015; Tutuş and Çiçekler, 2016; Akgül *et al*., 2018; Birinci *et al*., 2020; Letho *et al*., 2021) and PB (Gülsoy *et al*., 2016; Gülsoy and Şimşir, 2018; Çiçekler and Tutuş, 2019; Erkan *et al*., 2020; Çiçekler *et al*., 2021). Increases in pulp yield provide a significant economic contribution to the pulp mill. The addition of boron compounds also enables more effective use of forests (Gulsoy and Eroglu, 2011).

The reject ratios of pulps provide information about cooking liquor penetration into chips and pulping efficiency. The boron compounds added to pulps had a higher reject ratio (except for PB2 pulp). The reject ratios of pulps increased with the increasing addition ratio of boron compounds. The lowest and highest reject ratios were observed for SB-2 pulp (0.73 %) and PB-4 pulp (3.04 %), respectively (Table 3). E48, E67, and Col had a negative effect on the kraft pulps of *Populus tremula* and *Pinus nigra* (Kilic Pekgözlü *et al*., 2017). The reject ratio increases in the SB-added pulps were observed in the *Pinus nigra* (Gulsoy and Eroglu, 2011) and *Pteridium aquilinum* (Gülsoy and Şimşir, 2018) kraft pulping. On the contrary, some authors noted that SB addition caused reject ratio decreases (Ayata, 2008; Akgül and Temiz, 2006; Copur and Tozluoglu, 2008; Tutus *et al*., 2010a; Tutuş and Çiçekler, 2016). On the other hand, PB addition results in reject ratio decreases (Çiçekler and Tutuş, 2019; Erkan *et al*, 2020). On the contrary, PB caused the increase in the reject ratio of pulps (Gülsoy *et al*., 2016; Gülsoy and Şimşir, 2018; Çiçekler *et al*., 2021).

The kappa number of pulp is related to the effectiveness of pulping and the delignification degree of pulp. The boron compounds-added pulps had a higher kappa number (except for PB-2 and E48-2 pulps) than that of the control pulp. There was a linear relationship between the kappa number of pulps and the addition ratio of boron compounds. The lowest and highest kappa numbers were found in PB-2 (34.60) and Col-4 (46.60), respectively (Table 3). Kilic Pekgözlü *et al*. (2017) noted that the kappa number of *Populus tremula* and *Pinus nigra* kraft pulp was decreased with the addition of E48 and increased with the addition of E67. The authors also noted that the effect of Col addition on the kappa number of *Populus tremula* and *Pinus nigra* kraft pulps changed depending on tree species. SB addition result in increasing delignification (Copur and Tozluoglu, 2008; Ayata, 2008; Gulsoy and Eroglu, 2011; Aytekin, 2011; Birinci *et al*., 2020) and PB addition (Gülsoy and Şimşir, 2018; Çiçekler and Tutuş, 2019; Erkan *et al*., 2020). On the contrary, PB had an unfavorable effect on the kappa number of *Pinus pinaster* kraft pulp (Gülsoy *et al*., 2016). In addition, the kappa number of alkaline sulfite anthraquinone pulps of *Pinus pinea* (Gümüşkaya *et al*., 2011) and *Picea orientalis* (Erişir *et al*., 2015) decreased with SB additions.

The pulp viscosity indicates the degree of polymerization of polysaccharides. The addition of boron compounds resulted in pulp viscosity decreases. The increase in the addition ratios of boron compounds caused pulp viscosity increase. The lowest pulp viscosity was found in SB-2 pulp with 818.36 cm^3/g (Table 3). The cause of pulp viscosity decreases can be as-

Table 3 Properties of control and boron compounds-added pulps
Tablica 3. Svojstva kontrolnih uzoraka i celuloze s dodatkom spojeva bora

Cookings *Uzorci nakon kuhanja*	**Screened yield (A), %** *Prinos nakon prosijavanja (A), %*	**Reject, %** *Odbačeno, %*	**Total yield, %** *Ukupan prinos, %*	**Kappa number (B)** *Kappa broj (B)*	**Lignin in pulp (C: B*0.15), %** *Lignin u pulpi (C: B*0,15), %*	**Holocellulose in pulp (A-C), %** *Hemiceluloza u pulpi (A-C), %*	**Viscosity, cm^3/g** *Viskoznost, cm^3/g*
Control *Kontrolni uzorci*	45.67	0.92	46.59	35.07	5.26	40.41	980.64
PB-2	48.91	0.61	49.52	34.60	5.19	43.72	818.36
PB-4	52.05	3.04	55.09	46.07	6.91	45.14	931.00
SB-2	48.94	0.73	49.67	35.93	5.39	43.55	865.82
SB-4	48.93	1.37	50.30	37.50	5.63	43.31	957.39
E48-2	46.21	1.52	47.73	34.50	5.18	41.04	875.51
E48-4	46.63	2.09	48.72	35.47	5.32	41.31	904.79
E67-2	46.22	1.96	48.18	37.90	5.69	40.54	929.68
E67-4	45.51	2.58	48.09	41.60	6.24	39.27	948.71
Col-2	45.68	1.55	47.23	38.27	5.74	39.94	969.85
Col-4	46.31	2.81	49.12	46.60	6.99	39.32	975.26

cribed to higher hemicellulose retention in boron compounds-added pulps. Kilic Pekgözlü *et al*. (2017) noted that viscosity of *Populus tremula* kraft pulp was increased with the addition of E48, E67, and Col. The effect of PB on kappa number of *Pinus brutia* kraft pulp was statistically insignificant (Çiçekler and Tutuş, 2019). The authors noted that SB caused pulp viscosity decreases (Ayata, 2008; Copur and Tozluoglu, 2008; Tutus *et al*., 2010a). On the contrary, the others reported that SB additions (Akgül and Temiz, 2006; Tutus *et al*., 2010b; Birinci *et al*., 2020) and PB additions (Gülsoy and Şimşir, 2018; Erkan *et al*., 2020; Çiçekler *et al*., 2021) resulted in pulp viscosity increases.

The addition of all boron compounds caused tensile index increases (Figure 1). The highest tensile index increase of 26.27 % (from 68.02 Nm/g to 85.88 Nm/g) was determined in the E67-2 pulp. Otherwise, tensile index losses were observed in the PB-2 pulp. However, this strength loss was statistically insignificant (P>0.05). Furthermore, increasing the addition ratios of boron compounds (except for PB-4 pulp) caused tensile index increases. This result can be ascribed to an increase in the hemicellulose content of the boron compounds-added pulps. The hemicellulose with high hydrophilic properties causes the increase of strength properties of pulp (Kilic Pekgözlü *et al*., 2017). The fibers with higher hemicellulose content swell more easily and have high flexibility (Shin and Stromberg, 2007). Flexible fibers provide more contact areas with adjacent fibers, which leads to strong interfiber bonds (Forsström *et al*., 2005) and a high tensile index (Santos *et al*., 2008). Kilic Pekgözlü *et al*. (2017) reported that E48, E67, and Col caused a decrease in the tensile index of *Pinus nigra* kraft pulp. The authors also noted that the tensile index of E48, E67, and Col added pulps of *Populus tremula* was found to be higher than that of the control pulp. The losses in the tensile properties with SB addition (Akgül and Temiz, 2006; Copur and Tozluoglu, 2008; Gulsoy and Eroglu, 2011) and PB addition (Gülsoy *et al*., 2016) were reported in the literature. Conversely, some authors noted that SB (Ayata, 2008; Gülsoy and Şimşir, 2018) and PB (Gülsoy and Şimşir, 2018; Çiçekler and Tutuş, 2019) caused increases in the tensile properties of pulps.

The boron compounds-added pulps had a higher stretch ratio than that of the control pulp (Figure 2) (P<0.05). The highest stretch increase was obtained from E67-4 pulp with 21.78 % (from 2.02 % to 2.46 %). Kilic Pekgözlü *et al*. (2017) noted that E48 and E67 had a positive effect on the stretch ratio of *Pinus nigra* and *Populus tremula* kraft pulps. They also reported that Col addition caused the increase of the stretch ratio of *Populus tremula*, while it led to the decrease of the stretch ratio of *Pinus nigra*. Gülsoy and Şimşir (2018) noted that PB and SB had a positive effect on the stretch ratio of *Pteridium aquilinum* kraft pulps. İstek and Özkan (2008) stated that the stretch ratio of *Populus tremula* kraft pulp decreased with SB addition.

The addition of all boron compounds caused TEA increases. E67-4 pulp had the highest TEA increase with 36.69 % (from 77.24 J/m^2 to 105.58 J/m^2). Otherwise, TEA loss observed in the PB-2 pulp was statistically significant (P<0.05). Besides, increasing the addition ratios of E48, E67, and Col led to TEA increases (Figure 3). Kilic Pekgözlü *et al*. (2017) noted that TEA of *Populus tremula* handsheets increased with the addition of E48, E67, and Col (except for 8 % Col), while TEA of *Pinus nigra* handsheets decreased. Gülsoy and Şimşir (2018) noted that SB had a positive effect on the TEA of *Pteridium aquilinum* kraft pulp. The effect of SB on the TEA of *Populus tremula* kraft pulp was statistically insignificant (İstek and Özkan, 2008).

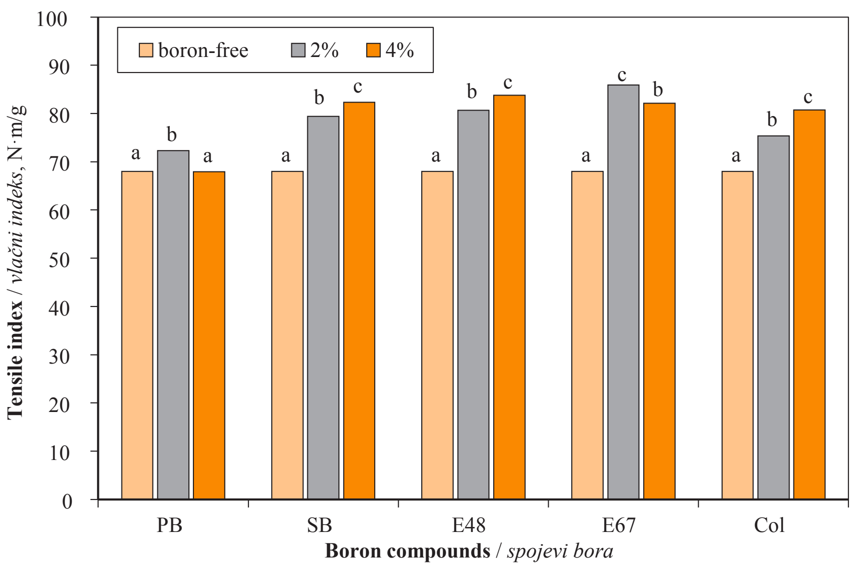

Figure 1 Effects of boron compounds on tensile index of pulps
Slika 1. Utjecaj spojeva bora na vlačni indeks celuloze

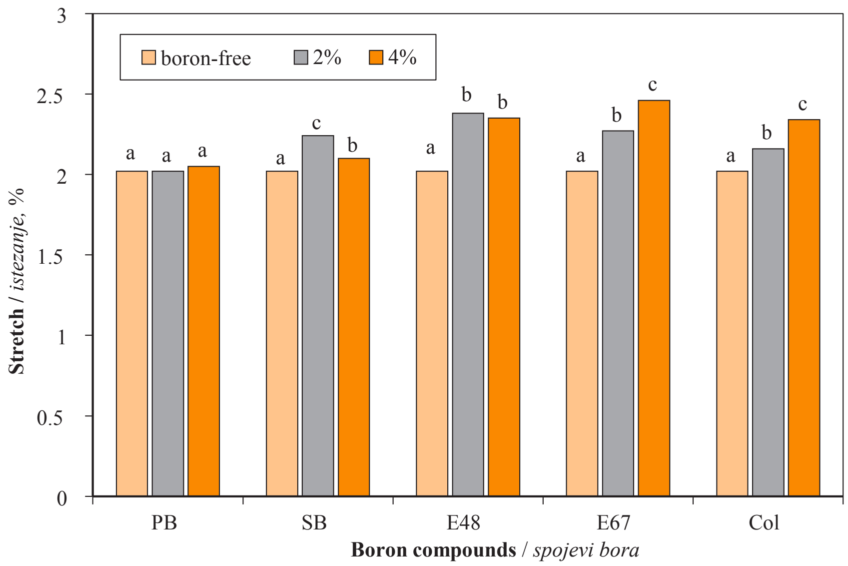

Figure 2 Effects of boron compounds on stretch of pulps
Slika 2. Utjecaj spojeva bora na istezanje celuloze

The addition of all boron compounds resulted in the burst index increases (P<0.05). The highest burst index increase was obtained from E48-4 pulp with 33.02 % (from 3.18 kPa·m^2/g to 4.23 kPa·m^2/g). Besides, the increasing addition ratios of SB and PB caused the burst index losses, while the increasing addition ratios of E48 led to the burst index increase. The effect of increasing addition ratios of E67 and Col on the burst index was statistically insignificant (P>0.05). The burst index increases can be ascribed to more hemicellulose retention in the course of pulping (Rydholm, 1965). Kilic Pekgözlü *et al*. (2017) stated that E48, E67, and Col had an unfavorable effect on the burst index of *Pinus nigra*, while they had a positive effect on the burst index of *Populus tremula*. The burst index losses with SB addition were determined in kraft pulp of *Abies bornmulleriana* (Akgül and Temiz, 2006), *Pinus brutia* (Copur and Tozluoglu, 2008), *Pinus nigra* (Gulsoy and Eroglu, 2011), poppy stems (Tutuş *et al*., 2011), and *Brassica napus* (Akgül *et al*., 2018). Conversely, some authors noted that SB addition caused the burst index increases in *Eucalyptus grandis* and *Eucalyptus camaldulensis* (Ayata, 2008), *Picea orientalis* (Tutus *et al*., 2010a), *Castanea sativa* (Aytekin, 2011), *Diospyros kaki* (Tutuş *et al*., 2014), *Prunus armeniaca* (Tutuş *et al*., 2016), and *Rhododendron luteum* and *Rhododendron ponticum* (Birinci *et al*., 2020) kraft pulps. PB had a positive effect on the burst index of *Pinus brutia* (Çiçekler and Tutuş, 2019) and *Pinus pinea* (Erkan *et al*., 2020). Conversely, PB addition led to burst index loss in the kraft pulp of *Pinus pinaster* (Gülsoy *et al*., 2016).

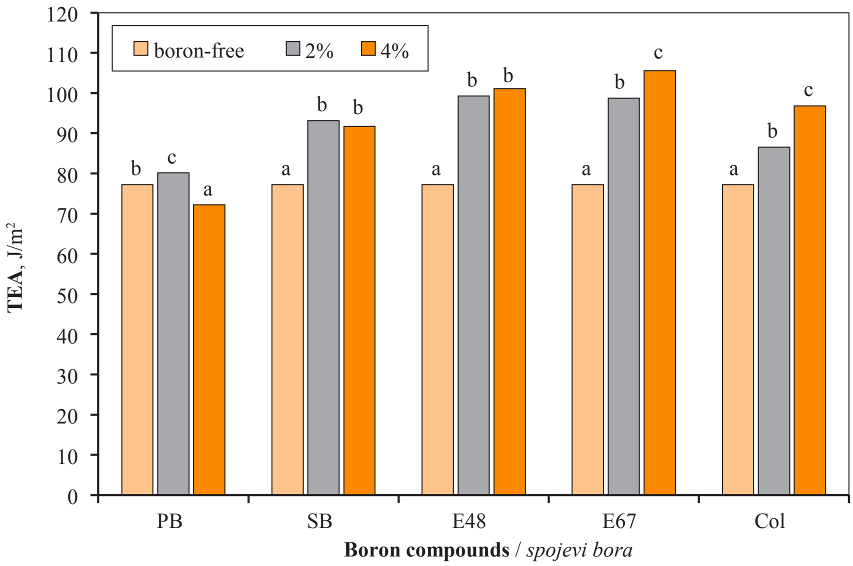

Figure 3 Effects of boron compounds on TEA of pulps
Slika 3. Utjecaj spojeva bora na TEA celuloze

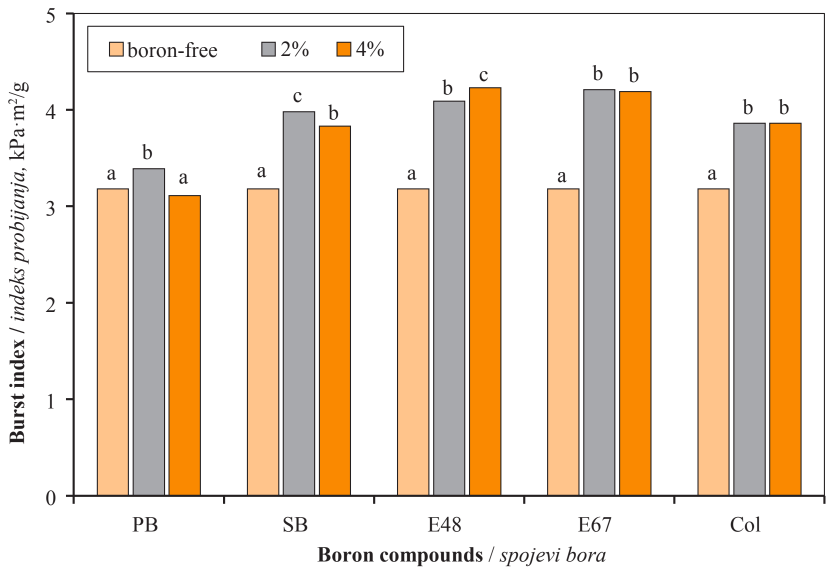

Figure 4 Effects of boron compounds on burst index of pulps
Slika 4. Utjecaj spojeva bora na indeks probijanja celuloze

All boron compounds caused the tear index increase (P<0.05). The highest tear index increase was obtained from E48-4 pulp with 37.55 % (from 5.30 mN·m^2/g to 7.29 mN·m^2/g). The increasing addition ratios of PB and E67 caused the tear index losses, while the effect of increasing addition ratios of SB, E48, and Col on the tear index was statistically insignificant (P>0.05). E48, E67, and Col had a positive effect on the tear index of *Pinus nigra* and *Populus tremula* pulps (Kilic Pekgözlü *et al*., 2017). The negative effect of PB on the tear index was reported by several authors (Gülsoy and Şimşir, 2018) and SB (Copur and Tozluoglu, 2008; Tutuş *et al*., 2011; Gulsoy and Eroglu, 2011; Akgül *et al*., 2018; Gülsoy and Şimşir, 2018). Tutuş and Çiçekler (2016) noted that, when 0.5 % $NaBH_4$ was added to the soda-oxygen pulping of wheat straw, the tear index values of the handsheets increased from 3.08 mN·m^2/g to 4.55 mN·m^2/g.

The addition of all boron compounds (except for E67 pulp) caused the pulp brightness increases (P<0.05). The lowest and highest brightness values were determined in E67-4 pulp with 18.00 % and SB-2 pulp with 21.35 %, respectively. The brightness of E67 pulp decreased in direct proportion to the increase of the E67 addition ratio. 2 % boron compounds addition caused the increase in handsheet brightness, while 4 % boron compounds addition led to the decrease in handsheet brightness. Kilic Pekgözlü *et al*. (2017) noted that E48 and Col had a positive effect on the handsheet brightness of *Pinus nigra*. On the contrary, E67 had a negative effect on the handsheet brightness of *Pinus nigra*. The authors also reported that the handsheet

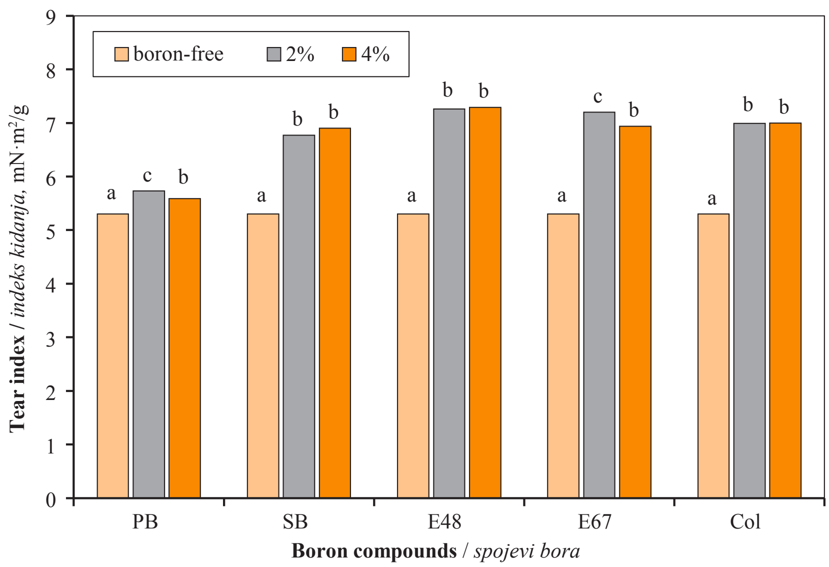

Figure 5 Effects of boron compounds on tear index of pulps
Slika 5. Utjecaj spojeva bora na indeks kidanja celuloze

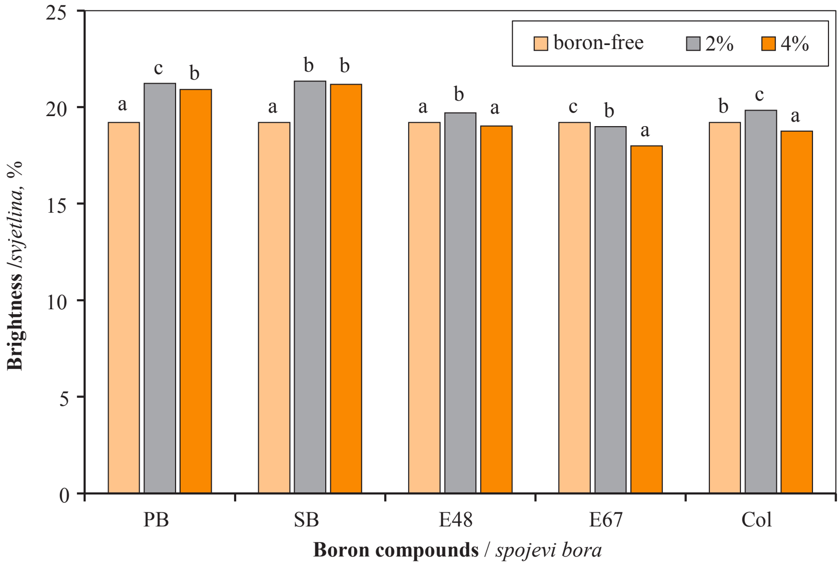

Figure 6 Effects of boron compounds on brightness of pulps
Slika 6. Utjecaj spojeva bora na svjetlinu celuloze

brightness of *Populus tremula* decreased with the addition of E48, E67, and Col. The brightness increases were reported by several authors in SB-added pulps (Akgül *et al*., 2007; Gulsoy and Eroglu, 2011; Tutuş *et al*., 2011, Tutuş *et al*., 2012; Tutuş *et al*., 2014, Tutuş and Çiçekler, 2016) and in PB-added pulps (Gülsoy *et al*., 2016; Gülsoy and Şimşir, 2018; Çiçekler and Tutuş, 2019). Conversely, Gümüşkaya *et al*. (2011) stated that SB had a negative effect on the brightness of alkali sulfite anthraquinone pulp of *Pinus pinea*.

4 CONCLUSIONS
4. ZAKLJUČAK

The results showed that boron compounds-added kraft pulping of Scots pine confers various advantages. The addition of boron compounds to kraft cooking liquor caused increases in screened and total yield of pulps. PB-4 pulp had the highest screened yield and total yield. The lowest reject ratio and kappa number were determined from PB-2 pulp. Besides, E67-4 pulp had the highest tensile properties of handsheets. In addition, the highest burst index and tear index values were obtained from E48-4 pulp. E48, E67, and Col are cheaper than PB and SB. The addition of these boron compounds resulted in relatively lower pulp yield than those of PB and SB pulps. However, they caused stronger pulps. E48, E67, and Col are cheaper than SB and PB. The effects of these boron compounds on the black liquor recovery process should be determined. The effects of E48, E67, and Col on other tree species, that are widely spread and important for the paper industry, should also be investigated.

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