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Combustion and Mechanical Properties of Wood Impregnated with Aqueous Solutions of Various Ammonium and Phosphate-Based Commercial Fertilizers

Gorivost i mehanička svojstva drva impregniranoga vodenim otopinama različitih komercijalnih gnojiva na bazi amonijaka i fosfata

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ABSTRACT • *This study evaluates the combustion and mechanical behavior of Oriental beech (Fagus orientalis L.) wood impregnated with aqueous solutions of various commercial fertilizers–specifically calcium ammonium nitrate (CAN), triple superphosphate (TSP), and their 1:1 weight-based mixture (CAN+TSP). These fertilizers were selected for their known flame-inhibiting potential due to their ammonium and phosphorus content. Ammonium dihydrogen phosphate (ADF), a widely accepted reference fire retardant, was included for comparison. Specimens were treated with 3 %, 6 %, and 9 % aqueous solutions of fertilizers and ADF and subjected to combustion testing based on ASTM E69, including measurements of mass loss, temperature, CO emissions, time to extinction, and collapse. Mechanical performance was assessed by determining modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) in accordance with TS and ISO standards. The results showed that 9 % solution of ADF yielded the most effective fire-retardant performance, with substantial reductions in mass loss and combustion temperature. In contrast, CAN treatments showed minimal improvement in flammability behavior. Mechanical degradation was evident at higher concentrations across all formulations, though 6 % solution of ADF and 3 % solution of CAN retained mechanical performance closest to untreated wood. These findings suggest that phosphate-rich fertilizers, especially ADF and TSP, may offer a viable and economical alternative to traditional fire retardants for wood, provided that impregnation concentration is carefully optimized to preserve mechanical integrity.*

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KEYWORDS: *wood impregnation; combustion; mechanical properties; ammonium dihydrogen phosphate (ADF); calcium ammonium nitrate (CAN); triple superphosphate (TSP)*

SAŽETAK • *U istraživanju su procijenjeni gorivost i mehanička svojstva drva kavkaske bukovine (Fagus orientalis L.) impregnirane vodenim otopinama različitih komercijalnih gnojiva – kalcij-amonijeva nitrata (CAN), trostrukog superfosfata (TSP) i njihove mješavine (CAN + TSP) u težinskom omjeru 1:1. Ta su gnojiva odabrana zbog svoga poznatog potencijala inhibicije plamena jer sadržavaju amonijak i fosfor. Za usporedbu rezultata u istraživanju je upotrijebljen amonijev dihidrogenfosfat (ADF) kao široko prihvaćeni referentni usporivač gorenja. Uzorci su tretirani 3-postotnim, 6-postotnim i 9-postotnim vodenim otopinama gnojiva i ADF-om te je ispitana njihova gorivost na temelju ASTM E69, uključujući mjerenja gubitka mase, temperature, emisije CO, vremena do trenutka gašenja i kolapsa. Mehanička su svojstva procijenjena određivanjem modula loma (MOR) i čvrstoće na tlak paralelno s vlakancima (CSPG), u skladu s TS i ISO standardima. Rezultati su pokazali da je 9-postotna otopina ADF-a najučinkovitije usporila gorenje, uz znatno smanjenje gubitka mase uzoraka i temperature izgaranja. Nasuprot tome, tretmani CAN-om rezultirali su minimalnim poboljšanjem u smislu smanjenja gorivosti. Mehaničko propadanje drva bilo je vidljivo pri višim koncentracijama svih formulacija, iako su primjenom 6-postotne otopine ADF-a i 3-postotne otopine CAN-a mehanička svojstva uzoraka zadržana najbližima netretiranom drvu. Ti rezultati pokazuju da gnojiva bogata fosfatima, posebno ADF i TSP, mogu biti održiva i ekonomična alternativa tradicionalnim usporivačima gorenja za drvo, uz uvjet da se koncentracija impregnacije pažljivo optimizira kako bi se očuvao mehanički integritet drva.*

KLJUČNE RIJEČI: *impregnacija drva; gorivost; mehanička svojstva; amonijev dihidrogenfosfat (ADF); kalcij-amonijev nitrat (CAN); trostruki superfosfat (TSP)*

1 INTRODUCTION
1. UVOD

Wood is a widely used natural material in both structural and non-structural applications within the fields of architecture, interior design, and civil engineering due to its favorable properties such as renewability, lightness, processability, aesthetic appeal, and thermal insulation (Reinprecht, 2016). Its use spans from structural systems to furniture and interior cladding in both residential and commercial environments (Baysal, 2011). However, despite these advantages, wood remains highly susceptible to biological and abiological degradation, particularly in humid environments or under elevated temperatures, which necessitates the application of protective treatments to enhance durability and safety (Yona *et al.,* 2021).

One of the most critical vulnerabilities of wood is its flammability. When exposed to heat, wood undergoes pyrolysis and produces combustible gases, tars, and smoke, which pose significant risks in fire scenarios (Lowden and Hull, 2013). In particular, smoke generation not only reduces visibility but also leads to suffocation hazards, especially in evacuation routes such as corridors and stairwells (Östman, 2006). Therefore, various fire-retardant treatments have been developed to reduce the spread of flames, lower heat release rates, and inhibit smoke production (Park and Baek, 2015; Lu *et al.,* 2020). Among these, inorganic salts such as ammonium sulfate, borates, and phosphates have shown promise due to their charring ability and flame inhibition (Le Van and Winandy, 1990; Atar *et al.,* 2004). However, issues such as leaching, corrosiveness, and ecological impact limit their widespread use (Wu *et al.,* 2021).

In recent years, ammonium and phosphate-based agricultural fertilizers have gained attention as low-cost alternatives for wood fire-retardant applications. These compounds are commonly available, water-soluble, and environmentally less aggressive compared to traditional chemicals (Baysal, 2011). Specifically, ammonium dihydrogen phosphate (ADF), calcium ammonium nitrate (CAN), and triple superphosphate (TSP) are known to contain fire-inhibiting elements such as ammonium and phosphorus, which facilitate char formation and limit thermal decomposition (Di Blasi *et al.,* 2008; Kol *et al.,* 2010). Studies have shown that wood impregnated with such fertilizers can exhibit improved resistance to combustion, with reduced mass loss and lower combustion temperatures (Gaff *et al.,* 2019; Lubloy *et al.,* 2021). However, the fire-retardant performance of these fertilizers varies by concentration and wood species, and limited research has compared them directly with standard fire-retardant chemicals such as ADF.

Beyond fire safety, a major consideration in the application of impregnating agents is their impact on the mechanical performance of wood. Water-soluble salt-based treatments can potentially compromise strength properties such as modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) due to chemical interactions with lignocellulosic components (Winandy, 1988; Mourant *et al.,* 2008). High pH levels and ion concentrations in salt solutions can lead to degradation of wood polymers, resulting in cell wall weakening, microstructural damage, and increased brittleness of wood (Borůvka *et al.,* 2016). Several studies have reported that impregnated wood specimens exhibit decreased bending strength and dimensional stability, particularly under high-temperature curing or prolonged exposure (Furuno *et al.,* 1992; Tomak *et al.,* 2012).

In addition to the widespread use of conventional salts, recent research has explored hybrid and bio-based formulations as emerging alternatives in wood fire protection. For instance, Ellis and Rowel (1989) demonstrated that oligomer phosphonates combined with diisocyanates can form durable fire-retardant coatings with minimal leaching. Similarly, Gašparík *et al.* (2017) found that thermal modification followed by fire-retardant treatment significantly reduced peak heat release rates in oak specimens. Moreover, Adetayo and Dahunsi (2019) reported that tropical hardwoods impregnated with low-cost local salts showed considerable resistance to structural collapse during fire tests. These developments align with growing interest in low-toxicity, environmentally friendly fire retardants that maintain mechanical integrity. Listyanto *et al.* (2020) further emphasized that combinations of borax and boric acid can yield synergistic improvements in fire resistance, even in hardwoods like mahogany. Meanwhile, Chanpirak *et al.* (2018) introduced microwave-assisted impregnation as a promising method to enhance the penetration of sulfur-containing ammonium salts in teak wood, demonstrating both improved retention and combustion performance. As techniques evolve, integrating fire performance with sustainability and material compatibility continues to be a critical research direction.

Given these challenges, this study aims to evaluate the fire-retardant and mechanical properties of Oriental beech (*Fagus orientalis* L.) wood impregnated with aqueous solutions of CAN, TSP, and their 1:1 mixture (CAN+TSP). ADF was included as a reference compound to benchmark performance. The main objectives are (1) to assess whether these commercial fertilizers can provide comparable fire-retardant performance to conventional chemicals, and (2) to examine their effects on the mechanical strength of wood. The findings of this research are expected to contribute to the development of low-cost, environmentally conscious, and structurally viable fire-retardant wood treatments suitable for applications in architectural interiors and beyond.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, three different fertilizer-based aqueous solutions were utilized for wood impregnation: calcium ammonium nitrate (CAN), triple superphosphate (TSP), and a 1:1 (by weight) mixture of both (referred to as CAN+TSP). These fertilizers were sourced from various commercial agrochemical suppliers located in the Muğla region of Turkey. The chemical ammonium dihydrogen phosphate (ADF), a widely used reference fire retardant, was also included in the experiments to provide a comparative benchmark.

Furthermore, prior research suggests that water-soluble salt-based impregnating agents may adversely affect the mechanical properties of treated wood. Therefore, alongside flammability tests, mechanical characterization including modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) was conducted to evaluate any potential degradation caused by the impregnation treatments.

Oriental beech (*Fagus orientalis* L.) wood was used as the substrate in all tests, and test specimens were prepared in accordance with relevant ASTM and TS ISO standards.

2.1 Impregnation method
2.1. Metoda impregnacije

According to ASTM D1413-07e1 (2016) standard, Oriental beech specimens were impregnated with 3 %, 6 %, and 9 % aqueous solutions of fertilizers. In this study, a vacuum desiccator was used for impregnation and connected to a vacuum pump via a vacuum trap. Before adding the solution to the chamber, a vacuum was applied at 101.325 Pa for 30 minutes, followed by an additional diffusion under vacuum at 101.325 Pa for 30 minutes.

After impregnation, retention amounts were calculated using Eq. 1:

$$Retention = \frac{G \cdot C}{V} \cdot 1000 \ (\text{kg/m}^3) \qquad (1)$$

Where;

$G = T_2 - T_1$ (g),

T_1 – Dry mass of Oriental beech specimens before impregnation (g),

T_2 – Mass of Oriental beech specimens after impregnation (g),

C – Percentage concentration of solution

V – Volume of specimens (cm^3).

2.2 Modulus of rupture (*MOR*)
2.2. Modul loma (*MOR*)

The modulus of rupture of wood specimens was performed according to ISO 13061-3 (2014). Wood specimens had been conditioned at 20 °C and 60 % RH for two weeks prior to testing. In this test, specimen dimensions were prepared as 20 mm × 20 mm × 360 mm (R×T×L). A total of 130 specimens were prepared, 10 specimens from each group. The *MOR* of wood specimens treated with chemicals were calculated using Eq. 2:

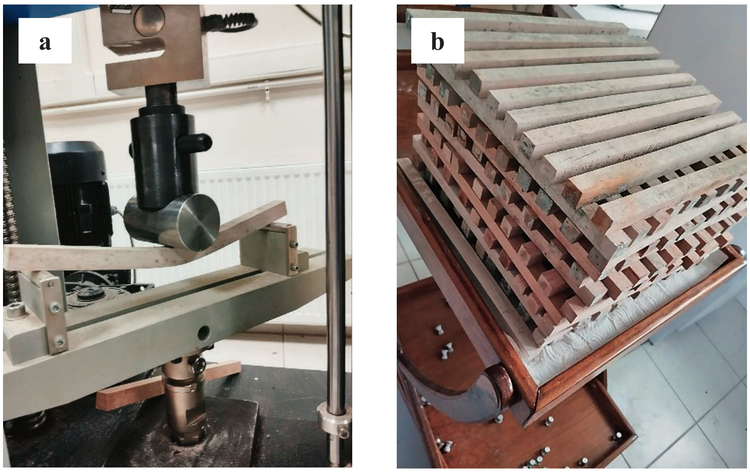

Figure 1 a) Three-point bending test setup; b) test specimens for *MOR* evaluation
Slika 1. a) Postav za ispitivanje savijanja u tri točke; b) uzorci za ispitivanje radi procjene *MOR*-a

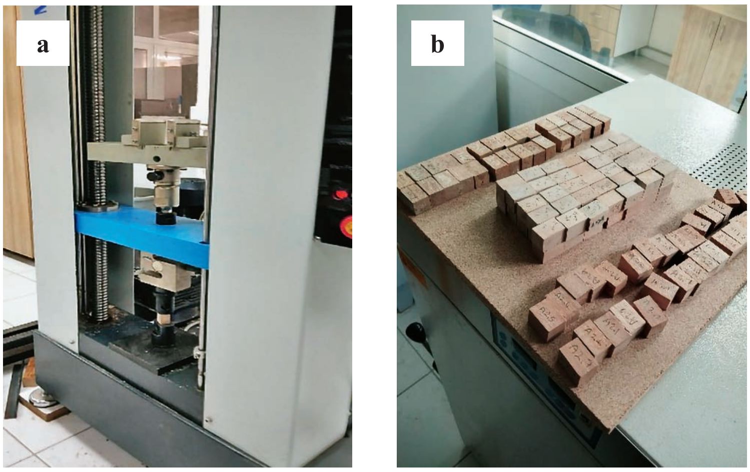

Figure 2 a) Compression strength test setup; b) CSPG wood specimens
Slika 2. a) Postav za ispitivanje tlačne čvrstoće; b) uzorci drva za ispitivanje čvrstoće na tlak paralelno s vlakancima

$$MOR = \frac{3 \cdot P \cdot I}{2 \cdot b \cdot h^2} \quad (\text{N/mm}^2) \qquad (2)$$

Where;
P – maximum load (N),
I – span (mm),
b – width of specimen (mm),
h – thickness of specimen (mm),
Y – deflection (mm).

The test setup and representative specimens used in the *MOR* measurements are shown in Figure 1.

2.3 Compression strength parallel to the grain (*CSPG*)
2.3. Čvrstoća na tlak paralelno s vlakancima (*CSPG*)

A universal testing machine (Marastek, Istanbul, Turkey) with a 4000 N load capacity was used to perform the *CSPG* test in compliance with ISO 13061-17 (2017). The testing procedure, which was controlled by software version M_tst_v17, employed a constant loading rate of 6 mm/min. All specimens were conditioned at 20 °C and 65 % relative humidity for 2 weeks before *CSPG* test. In this test, specimen dimensions were prepared as 20 mm × 20 mm × 30 mm (R×T×L). A total of 130 specimens were prepared, 10 specimens from each group. *CSPG* were calculated using Eq. 3:

$$CSPG = \frac{P}{a \cdot b} \quad (\text{N/mm}^2) \qquad (3)$$

Where;
P – load at break (N),
a, b – specimen cross-section dimensions (mm).

The test setup and representative specimens used in the compression strength measurements are shown in Figure 2.

2.4 Combustion test method
2.4. Metoda ispitivanja gorivosti

The combustion characteristics of the impregnated wood specimens were evaluated in accordance with ASTM E69-02 (2002), standard test method for combustion characteristics of large pieces of wood. Test specimens with dimensions of 9 mm × 19 mm × 1019 mm were vertically positioned inside a steel combustion tube equipped with a gas burner, simulating real fire exposure for the initial four minutes of testing. The combustion behavior was observed after the ignition phase and the removal of the flame source. A calibrated Testo 340 flue gas analyzer (Testo SE & Co. KGaA, Lenzkirch, Germany) was used to quantify the concentration of carbon monoxide (CO) in the combustion gases.

Measurements of temperature (°C) and carbon monoxide (CO) were recorded at 30-second intervals until the complete extinction of visible flames and structural collapse of the specimen. In addition, the time to flame extinction and time to collapse were manually recorded using a stopwatch.

To evaluate the flame-retardant effectiveness of the applied chemicals, key indicators such as mass loss, combustion duration, peak temperature, and CO emissions were analyzed. Weight loss due to combustion was calculated using Eq. 4:

$$R\,(\%) = \frac{M_a - M_b}{M_b} \cdot 100 \tag{4}$$

Where;
M_b – Dry mass of test specimen before impregnation (g),
M_a – Dry mass of test specimen after impregnation (g).

All tests were conducted under identical ventilation and environmental conditions to ensure consistency. The test setup and representative specimens are illustrated in Figure 3.

2.5 Statistical analysis
2.5. Statistička analiza

Variance analysis was used to determine the statistical differences between the data collected for the study, which were examined using the statistical package SPSS program at a 95 % confidence level. The factors between which the discrepancies existed were identified using the Duncan test.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Results of modulus of rupture
3.1. Rezultati ispitivanja modula loma

MOR test results (Table 1) revealed statistically significant differences between the control and treatment samples. The untreated control sample exhibited the highest *MOR* (110.221 N/mm^2), establishing a reference for mechanical integrity. Among the treated specimens, ADF of 3 % (94.246 N/mm^2) and CAN of 3 % (95.750 N/mm^2) demonstrated values closest to the control and were classified in homogeneity group B, indicating that low-concentration impregnation had a relatively limited impact on *MOR*.

However, as the impregnation concentrations increased, a progressive decline in *MOR* values was observed. For instance, CAN of 6 % and CAN of 9 % decreased to 79.878 N/mm^2 and 74.935 N/mm^2, respectively. A similar trend was evident in the TSP group, with TSP of 9 % falling to 79.907 N/mm^2. These results suggest a concentration-dependent weakening of the wood matrix, likely due to the disruption of lignocellulosic structures by high levels of water-soluble salts. Such treatments can alter fiber adhesion and microfibril arrangement, leading to mechanical degradation (Borůvka *et al.,* 2016; Mourant *et al.,* 2008). Baysal *et al.,* (2013) also reported that wood specimens treated with waterborne chemicals such as boron compounds exhibited a reduction in mechanical properties, including MOR.

Among all formulations, ADF of 6 % maintained a relatively high *MOR* value (92.418 N/mm^2) with the lowest coefficient of variation (2.454 %), indicating consistent performance and suggesting that phosphate-based compounds, when used at moderate levels, may ensure effective penetration without significantly com-

Figure 3 a) Vertical combustion test setup; b) flammability test wood specimens
Slika 3. a) Postav vertikalnog testa gorivosti; b) uzorci drva za ispitivanje gorivosti

Table 1 *MOR* values
Tablica 1. Vrijednosti modula loma

Chemicals *Kemikalije*	**Concentrations, %** *Koncentracija, %*	**Retention value, kg/m³** *Retencija,* kg/m³	***MOR*, N/mm²**	**Standard deviation** *Standardna devijacija*	**Coefficient of variation** *Koeficijent varijacije*	**Homogeneity group** *Homogenost skupina*
Control	-	-	110.221	13.657	12.390	A
ADF	3	12.48	94.246	11.948	12.677	B
ADF	6	23.69	92.418	2.268	2.454	BC
ADF	9	33.53	84.232	5.520	6.553	C
CAN	3	12.97	95.750	13.096	13.677	B
CAN	6	27.93	79.878	4.267	5.341	CD
CAN	9	41.73	74.935	6.685	8.921	D
TSP	3	11.56	90.546	10.746	11.868	BC
TSP	6	27.26	84.127	20.286	24.113	C
TSP	9	32.97	79.907	4.195	5.249	CD
CAN+TSP	3	12.46	83.161	11.515	13.846	CD
CAN+TSP	6	20.87	80.485	5.108	6.346	CD
CAN+TSP	9	45.06	75.430	6.553	8.687	D

ADF – Ammonium dihydrogen phosphate, CAN – calcium ammonium nitrate, TSP – Triple superphosphate
ADF – *amonijev dihidrogenfosfat,* CAN – *kalcij-amonijev nitrat,* TSP – *trostruki superfosfat*

promising structural cohesion (Kol *et al.*, 2010). In contrast, TSP of 6 %, despite a comparable MOR value (84.127 N/mm²), exhibited the highest coefficient of variation (24.113 %), indicating inconsistent distribution or retention. This inconsistency is likely due to the high solubility and potential leaching behavior of phosphate salts during drying, a phenomenon also highlighted by Tomak *et al*. (2012).

Mixture groups (K+T1) also followed similar trends, with increasing concentrations resulting in lower *MOR* values and moderate coefficient of variation. The K+T1 of 9 % group, with 75.430 N/mm² was placed in homogeneity group D, further confirming the negative impact of high impregnation levels.

Overall, the findings emphasize that high concentrations of CAN and TSP significantly reduce *MOR* of Oriental beech, while moderate ADF treatments, particularly at 6 % concentration, maintain mechanical performance within acceptable limits. The data reinforce the importance of optimizing the impregnation concentration to achieve a balance between fire-retardant efficacy and mechanical reliability.

3.2 Compression strength parallel to the grain (*CSPG*) results
3.2. Rezultati ispitivanja čvrstoće na tlak paralelno s vlakancima

CSPG results (Table 2) revealed statistically significant differences between the control and treated samples. The control sample exhibited the highest average compression strength (57.073 N/mm²), serving as the benchmark for untreated wood. Among the treated specimens, TSP of 3 % (44.080 N/mm²) achieved the highest *CSPG* and was classified in homogeneity group B, suggesting that phosphate-based impregnation at this concentration can maintain a satisfactory level of mechanical integrity.

In contrast, higher concentrations of ADF and CAN resulted in a marked reduction in compression strength. ADF of 9 % (30.395 N/mm²) and CAN of 9 % (30.867 N/mm²) were placed in the CD group, indicating substantial mechanical degradation. These findings align with previous studies reporting that excessive salt retention may disrupt the wood microstructure through osmotic stress and chemical interaction with lignin and hemicellulose, ultimately compromising load-bearing capacity (Mourant *et al.,* 2008; Baysal *et al.,* 2013; Borůvka *et al.,* 2016).

Intermediate values were observed in CAN of 3 %, TSP of 3 %, and CAN+TSP of 3 %, ranging between 39.498 – 44.080 N/mm². Although statistically lower than the control, these treatments may be considered structurally acceptable for non-load-bearing or interior architectural applications. The performance of TSP of 3 %, in particular, supports the notion that phosphate-based treatments, when properly dosed, are less detrimental to the compressive behavior of wood (Kol *et al.,* 2010).

These outcomes confirm a concentration-dependent mechanical impact, where excessive retention leads to internal stress and weakening. This effect was more severe in ADF and CAN treatments, suggesting a need for controlled formulation.

Overall, the results highlight a clear trade-off between fire retardancy and mechanical performance. While high ADF concentration offers superior flame resistance (as discussed in Section 3.3), they may not be suitable for structural components.

Table 2 *CSPG* values
Tablica 2. Vrijednosti čvrstoće na tlak paralelno s vlakancima

Chemicals *Kemikalije*	**Concentrations, %** *Koncentracija, %*	**Retention value, kg/m³** *Retencija,* kg/m³	***CSPG*, N/mm²**	**Standard deviation** *Standardna devijacija*	**Coefficient of variation** *Koeficijent varijacije*	**Homogeneity group** *Homogenost skupina*
Control	-	-	57.073	5.202	9.114	A
ADF	3	13.12	37.387	1.655	4.426	C
ADF	6	25.72	36.048	2.467	6.843	C
ADF	9	48.45	30.395	1.781	5.859	CD
CAN	3	15.03	39.498	5.447	13.790	BC
CAN	6	32.13	33.201	2.187	6.587	C
CAN	9	44.91	30.867	3.703	11.996	CD
TSP	3	11.52	44.080	5.313	12.053	B
TSP	6	29.95	37.343	3.048	8.162	BC
TSP	9	44.34	39.471	3.142	7.960	BC
CAN+TSP	3	14.22	41.728	5.936	14.225	B
CAN+TSP	6	26.19	38.496	4.796	12.458	BC
CAN+TSP	9	43.58	34.681	4.703	13.560	C

ADF – Ammonium dihydrogen phosphate, CAN – calcium ammonium nitrate, TSP – Triple superphosphate
ADF – *amonijev dihidrogenfosfat*, CAN – *kalcij-amonijev nitrat*, TSP – *trostruki superfosfat*

3.3 Combustion results
3.3. Rezultati ispitivanja gorivosti

3.3.1 Retention amounts
3.3.1. Retencija

Table 3 summarizes the retention values (kg/m³) of the fertilizer-based impregnation solutions applied to wood. Retention amount is a key indicator of how much active compound remains within the wood after treatment and directly influences the fire-retardant efficiency and potential mechanical impacts of the process.

As expected, retention values increased proportionally with solution concentration across all treatment samples, confirming the effectiveness and consistency of the applied vacuum-pressure impregnation method. The highest retention was recorded in the CAN+TSP of 9 % concentration group (50.26 kg/m³), followed by ADF of 9 % (48.33 kg/m³), and CAN of 9 % concentration (46.12 kg/m³). The lowest value was observed in ADF of 3 % concentration (13.60 kg/m³). These results align with previous studies showing that phosphate- and nitrate-based compounds, due to their high-water solubility and ionic structure, penetrate wood tissues efficiently (Kartal *et al.,* 2009; Kol *et al.,* 2010).

However, while high retention enhances fire resistance by increasing the availability of fire-retardant chemicals in the wood matrix, it may also result in mechanical degradation. As shown in previous sections, samples with high retention values – particularly ADF at 9 % and CAN at 9 % – exhibited notable reductions in both *MOR* and *CSPG*. This supports the existing evidence that high salt concentrations can disrupt cell wall integrity, alter lignocellulosic bonding, and increase brittleness, especially at elevated impregnation levels (Borůvka *et al.,* 2016; Mourant *et al.,* 2008).

In summary, retention values are essential for predicting both combustion resistance and mechanical impact in impregnated wood. The findings suggest that optimal fire-retardant performance requires a balanced concentration: one that ensures effective retention without compromising mechanical integrity. Further research may focus on hybrid systems or controlled-release formulations that optimize this balance for practical applications.

3.3.2 Mass losses after combustion
3.3.2. Gubitak mase izmjeren nakon gorenja

As shown in Table 4, the control sample exhibited the highest mass loss (92.73 %), reflecting the natural flammability of untreated wood. In contrast, the ADF of 9 % concentration recorded the lowest mass loss (38.05 %), followed by ADF of 6 % (69.28 %), and ADF of 3 % (73.04 %), indicating a clear dose-depend-

Table 3 Retention amounts of impregnation chemicals
Tablica 3. Retencija impregnacijskih kemikalija

Chemicals *Kemikalije*	**Concentrations, %** *Koncentracija, %*	**Retention, kg/m³** *Retencija,* kg/m³
TSP	3	15.30
TSP	6	37.21
TSP	9	43.03
CAN	3	15.99
CAN	6	36.32
CAN	9	46.12
ADF	3	13.60
ADF	6	25.38
ADF	9	48.33
CAN+TSP	3	15.03
CAN+TSP	6	27.10
CAN+TSP	9	50.26

Table 4 Mass losses data of impregnated wood specimens
Tablica 4. Podatci o gubitku mase impregniranih uzoraka drva

Chemicals *Kemikalije*	**Concentration, %** *Koncentracija, %*	**Mass loss, %** *Gubitak mase, %*	**Std. Dev.**	**Min.**	**Max.**	**Homogeneity group** *Homogenost skupina*
Control	-	92.73	2.59	89.37	95.68	H
TSP	3	77.99	1.32	76.63	79.44	DE
TSP	6	77.58	1.05	76.64	79.09	DE
TSP	9	74.28	1.70	72.83	76.45	CD
CAN	3	88.98	1.68	86.85	90.92	H
CAN	6	88.80	1.43	86.84	89.84	H
CAN	9	90.30	1.37	88.78	91.88	H
ADF	3	73.04	2.05	71.09	75.59	C
ADF	6	69.28	3.96	64.59	73.30	B
ADF	9	38.05	5.67	29.76	42.35	A
CAN+TSP	3	82.03	2.11	80.01	84.55	G
CAN+TSP	6	79.02	3.43	75.38	83.02	EF
CAN+TSP	9	79.70	1.59	77.50	81.26	FG

Table 5 Results measured during combustion
Tablica 5. Rezultati izmjereni tijekom gorenja

Chemicals *Kemikalije*	**Concentration, %** *Koncentracija, %*	**Time to collapse, min** *Vrijeme do kolapsa,* min	**Time to fade out, min** *Vrijeme do kraja gorenja,* min	**Temperature, °C** *Temperatura, °C*			**CO, ppm**		
		Mean (std. dev.)	Mean (std. dev.)	Mean	Max.	Min.	Mean	Max.	Min.
Control	-	4.39 (0.17)	5.28 (0.71)	117.86	166.70	52.50	42.65	82.00	13.00
TSP	3	3.57 (0.37)	4.33 (0.26)	125.92	155.40	110.70	9.41	21.00	3.00
TSP	6	3.50 (0.36)	4.78 (0.50)	114.90	161.40	49.30	12.06	51.00	3.00
TSP	9	3.38 (0.15)	4.63 (0.43)	104.33	123.70	84.10	12.19	26.00	2.00
CAN	3	3.63 (0.55)	4.38 (0.19)	105.44	154.70	34.00	36.30	70.00	6.00
CAN	6	3.21 (0.17)	3.67 (0.25)	106.99	155.30	34.30	37.38	63.00	20.00
CAN	9	2.86 (0.39)	4.22 (0.16)	129.71	151.50	109.90	52.65	90.00	24.00
ADF	3	4.26 (0.46)	5.21 (0.58)	88.70	116.50	66.70	44.55	98.00	13.00
ADF	6	4.31 (0.18)	5.00 (0.46)	90.59	116.80	74.00	32.90	92.00	7.00
ADF	9	3.85 (0.24)	3.86 (0.25)	58.82	85.40	38.80	20.71	39.00	5.00
CAN+TSP	3	3.44 (0.40)	4.02 (0.31)	127.53	147.90	108.40	19.26	59.00	5.00
CAN+TSP	6	3.90 (0.40)	4.49 (0.34)	112.29	148.00	25.60	20.18	73.00	4.00
CAN+TSP	9	4.18 (0.21)	4.88 (0.86)	98.13	153.90	20.90	17.23	59.00	3.00

ent flame-retardant effect of ammonium dihydrogen phosphate. These results align with previous findings that phosphate-based treatments enhance char formation and suppress volatile release, thereby reducing combustion (Di Blasi *et al.,* 2008; Gaff *et al.,* 2019).

Among other treatments, TSP of 9 % concentration showed moderate effectiveness (74.28 %), while CAN at 9 % remained close to the control (90.30 %), suggesting that nitrate-based compounds lack sufficient charring capacity and may even contribute oxidizing effects during combustion (Wu *et al.,* 2021). The CAN+TSP combinations showed intermediate mass losses (79.02–82.03 %), indicating limited synergistic behavior between nitrate and phosphate compounds.

3.3.3 Thermal and gas emission behavior
3.3.3. Emisija topline i plinova

In addition to mass loss, fire performance was evaluated based on extinction time, collapse time, combustion temperature, and carbon monoxide (CO) release (Table 5).

The ADF of 9 % concentration group demonstrated the shortest extinction time (3.86 min) and lowest average combustion temperature (58.82 °C), confirming its superior fire suppression capability through endothermic decomposition and char layer formation (Lowden and Hull, 2013). In contrast, CAN+TSP of 3 % exhibited the highest combustion temperature (127.53 °C), indicating limited heat suppression.

Regarding CO emissions, TSP of 3 % concentration released the lowest amount (9.41 ppm), while ADF of 3 % showed the highest (44.55 ppm). However, CO levels dropped substantially at higher ADF concentrations, with ADF of 9 % emitting only 20.71 ppm, consistent with improved gas-phase suppression. This trend supports findings that higher phosphorus content improves combustion stability (Gaff *et al.,* 2019).

3.3.4 Overall evaluation of fire-retardant effectiveness
3.3.4. Ukupna procjena učinkovitosti usporivača gorenja

Among all treatments, ADF at 9 % concentration provided the most comprehensive fire-retardant performance, significantly reducing mass loss, combustion temperature, and toxic gas emission, while ensuring fast flame extinction. In comparison, TSP treatments, especially at higher concentration, offered moderate protection with better mechanical preservation (as discussed earlier). CAN-based and CAN+TSP combinations showed limited flame-retardant capacity, underlining the importance of chemical composition as well as concentration in fire safety optimization.

4 CONCLUSIONS
4. ZAKLJUČAK

This study evaluated the effects of various commercial fertilizer-based aqueous impregnation solutions – namely calcium ammonium nitrate (CAN), triple superphosphate (TSP), their 1:1 mixture (CAN+TSP), and a reference chemical (ammonium dihydrogen phosphate, ADF) – on the fire-retardant and mechanical properties of Oriental beech (*Fagus orientalis* L.) wood.

The experimental results demonstrated that:

ADF of 9 % concentration showed the most effective flame-retardant behavior, significantly reducing mass loss, combustion temperature, and extinction time.

CAN treatments, across all concentrations, provided negligible fire-retardant performance and led to substantial mechanical degradation at higher concentrations.

The combination of CAN and TSP (CAN+TSP) showed intermediate fire behavior but did not provide clear synergistic advantages over individual formulations.

Modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) were both adversely impacted mechanically by all high-concentration treatments. The formulations containing 6 % ADF and 3 % CAN had the least negative effects on the mechanical characteristics.

These findings suggest that phosphate-based compounds, particularly ADF and to some extent TSP, may serve as cost-effective and partially sustainable fire-retardant alternatives, provided their concentrations are carefully optimized. However, a trade-off remains between fire protection and mechanical performance, highlighting the need for tailored formulations depending on the intended end-use of the treated wood – structural or non-structural.

Further research should focus on the long-term durability, leaching resistance, and environmental impacts of these fertilizer-based treatments, as well as the development of hybrid or encapsulated systems to improve performance without compromising mechanical integrity.

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