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Improving durability and mechanical resistance of wood/plastic composites through boric acid treatment

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ABSTRACT: In this study, the effects of boric acid (BA) treatment on the mechanical properties and decay resistance of poplar wood flour/polypropylene composites (WPCs) were investigated. Three composite groups were prepared: untreated WPC (UT-WPC), BA-treated WPC with in-process powder addition (BA-T-WPC), and BA-pretreated WPC using aqueous BA solution (BA-PT-WPC). Mechanical properties including flexural strength and modulus, tensile strength and modulus, hardness, and impact strength were evaluated before and after exposure to fungal decay (*Trametes versicolor*). The results showed that boric acid treatment improved several mechanical properties of undecayed WPC. Specifically, BA-T-WPC exhibited the highest flexural strength (50.77 MPa) and modulus (3473 MPa), while BA-PT-WPC demonstrated superior tensile modulus (4563 MPa) and impact strength (49.40 J/m). Decay exposure decreased all mechanical properties across all groups, although BA-treated samples retained slightly higher performance compared to the untreated control. These findings suggest that boric acid can effectively enhance the mechanical behavior and decay resistance of WPCs through both direct and pretreatment methods.

Keywords: WPC, poplar wood, boric acid, durability, physical and mechanical resistance

Ahşap/plastik kompozitlerin dayanıklılığı ve mekanik direncinin borik asit uygulamasıyla artırılması

ÖZ: Bu çalışmada, borik asit (BA) işleminin kavak odun unu/polipropilen kompozitlerinin (WPC'ler) mekanik özellikleri ve çürümeye karşı direnci üzerindeki etkileri araştırılmıştır. Üç kompozit grubu hazırlanmıştır: işlenmemiş WPC (UT-WPC), işlem sırasında toz halinde BA ilave edilerek hazırlanmış WPC (BA-T-WPC) ve sulu BA çözeltisiyle ön işlem uygulanmış WPC (BA-PT-WPC). Eğilme direnci, eğilme modülü, çekme direnci,çekme modülü, sertlik, ve darbe direnci gibi mekanik özellikler Trametes versicolor mantarıyla çürütme öncesi ve sonrası değerlendirilmiştir. Sonuçlar, borik asit işleminin çürümemiş WPC'nin bazı mekanik özelliklerini geliştirdiğini göstermiştir. Özellikle, BA-T-WPC en yüksek eğilme direnci (50.77 MPa) ve modülünü (3473 MPa) sergilerken, BA-PT-WPC en yüksek çekme modülü (4563 MPa) ve darbe dayanımı (49.40 J/m) göstermiştir. Çürümeye maruz kalma tüm gruplarda mekanik özellikleri azaltmış olsa da, BA ile muamele edilmiş örnekler, işlem görmemiş kontrol grubuna kıyasla biraz daha yüksek performans göstermiştir. Bu bulgular, borik asidin hem doğrudan hem de ön işlem yoluyla WPC'lerin mekanik davranışını ve çürümeye karşı direncini etkili bir şekilde artırabileceğini göstermektedir.

Anahtar kelimeler: WPC, kavak ağacı, borik asit, dayanıklılık, fiziksel ve mekanik direnç

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1 Introduction

Wood plastic composites (WPCs) are important and promising engineered wood products that are widely used in areas like landscaping, transportation, municipal engineering, and construction. Wood plastic composites (WPCs) have advanced significantly within the thermoplastic industry, being utilized in a variety of applications such as interior automotive panels, garbage containers, crates, and garden tools (Hornsby et al., 1997). They have also seen substantial development in exterior nonstructural or semi-structural building products, including door and window frames, siding, decking, cladding, floor and roof tiles, and fencing (Schneider et al., 2000).

They incorporate natural fibers, including wood flour, pulp fibers, and cellulose fibers, to reinforce thermoplastics such as polyethylene (both high and low density), polypropylene, and PVC. The appeal of using these natural fibers lies in several advantages, including reduced production costs and density, simplified preparation processes, lower energy consumption during processing, biodegradability, and broader applicability compared to traditional reinforcing fibers like glass and carbon (Chaharmahali et al., 2010).

WPCs are recognized for their excellent durability, dimensional stability, high rigidity, and relatively low density (Schneider et al., 2000; Ashori, 2008). However, their broader adoption is significantly limited due to their inadequate fire resistance (Mouritz and Gibson, 2006; Chapple and Anandjiwala, 2010).

In light of the global crisis regarding the scarcity of forestry and fossil oil resources, projections suggest that the use of natural fiber-reinforced composites is expected to increase from 12% in 2010 to 18% by 2020, and further to 25% by 2030 (Gurunathan et al., 2015). As the demand for engineered wood products rapidly increases across various applications, wood plastic composites (WPCs) have emerged as a leading type of natural fiber-reinforced composite. WPCs are primarily made from thermoplastic polymers such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS), combined with biomass particles and fibers sourced from forestry and agricultural waste, including wood, bamboo, straw, stalks, husks, and bast. These materials are regarded as essential and innovative options for both residential and industrial construction (Adhikary, 2011).

Borates offer several benefits as wood preservatives. They not only provide flame retardation but also protect against organisms that damage wood, possess low toxicity to mammals, and have low volatility. Additionally, borates are both colorless and odorless and non-corrosive, have been utilized for many years as low-toxicity wood preservatives mainly to enhance biological resistance and thermal stability in wood (Murphy, 1990; Drysdale, 1994; Chen et al., 1997; Yalinkilic et al., 1997). However, they tend to leach from treated wood that is in contact with the ground during rainfall (Yalinkilic et al., 1997). As a result, boron compounds are primarily used in indoor settings. The future use of boron preservatives relies on enhancing their stability in wood for effective protection over a significant duration (Nicholas et al., 1990) and improving the negative characteristics of boron-treated wood through additional treatments (Yalinkilic et al., 1997). Consequently, the combination of borates with other preservatives has been thoroughly studied for outdoor wood preservation (Devi and Maji, 2007; Murphy et al., 1995).

Fruno et al., (1993) explored the use of boron compounds, including boric acid, borax, boron trioxide, ammonium borate, and potassium borate, to create insoluble organic substances in wood through a reaction with water glass acid treatment. They discovered that utilizing the water glass-boron compound system enabled the formation of a composite material that offered improved dimensional stability, reduced hygroscopicity, and enhanced fire resistance. Bal et al., (2023) found that increasing wood flour in composite boards made from waste plastic furniture parts decreased flexural and tensile strengths and elongation, while increasing density, hardness, and stiffness. TGA and DSC analyses showed the plastics mainly consisted of LLDPE and PP, with decomposition temperatures rising as wood flour content increased.

Thermal treatment of wood flour affects the physico-mechanical properties of wood plastic composites, with some improvements in strength and reduced water uptake at specific temperatures and durations. Fungal decay generally decreased mechanical properties, but treated samples showed better resistance in moisture-related parameters compared to decayed ones (Hosseinihashemi and Arwinfar, 2023). Baysal et al., (2007) examined the physical, biological, mechanical, and fire properties of wood polymer composites (WPC) made from vinyl monomers such as styrene (ST), methylmethacrylate (MMA), and a 50:50 mixture of the two, using treated sapwood from Scots pine (*Pinus sylvestris* L.). They first impregnated the wood with a 1% concentration of a boric acid (BA) and borax (BX) mixture before applying the monomer treatment. Their findings indicated that the vinyl monomers significantly improved the physical properties of the wood, resulting in increased anti-swelling efficiency (ASE), specific gravity (SG), and decreased water absorption (WA). Furthermore, the modulus of elasticity (MOE) and modulus of rupture (MOR) for the treated samples surpassed those of untreated control specimens. Although the ASE, MOE, and MOR for the WPC pre-impregnated with the BA and BX mixture were somewhat diminished, its fire resistance was enhanced. Bal (2022) investigated the production of wood plastic composites (WPCs) using a flat pressing method without an extruder, utilizing linear low-density polyethylene and pine wood flour with varying filler rates (0%, 10%, 20%, 30%, and 40%). Results indicate that increasing wood flour content enhances density, bending strength, and stiffness, while reducing elongation at break, highlighting the effects of filler percentage on WPC performance.

The aim of this study was to investigate the effect of boric acid (BA) treatment on the decay, water, and mechanical resistance performances of impregnated beech wood flour (WF) filled polypropylene composites.

2 Material and Method

2.1 Polymer matrix, reinforcing filler, coupling agent, and preservative

Poplar wood flour (PWF) was used as the lignocellulosic filler and sourced from the Amol farms of Iran. The thermoplastic matrix was polypropylene (PP) with a melt flow index of 10 g/10 min, supplied by the Tabriz Petrochemical Company of Iran. The maleic anhydride polypropylene (MAPP) from Eastman Chemical Products, Inc., as Epolene G-3003^{TM} polymer with 8% acid anhydride and a molecular weight of 103.500 was used as a compatibilizer to improve adhesion between the hydrophilic wood flour and the hydrophobic PP matrix. Boric acid (H_3BO_3, ≥99% purity) was obtained from laboratory of Department of Wood Science and Paper Technology, Ka.C., Islamic Azad University.

2.2 Composite formulation

The formulations of the composite materials are presented in Table 1. Three groups were prepared:

UT-WPC: Untreated poplar wood flour/polypropylene composite, containing 40 wt% PWF, 58 wt% PP, and 2 wt% MAPP.

BA-T-WPC: Composite with boric acid added as powder (1 wt%) during the mixing process (treated in-process).

BA-PT-WPC: Composite containing boric acid-pretreated wood flour soaked in a 1 wt% aqueous solution of boric acid and oven-dried prior to compounding.

Table 1. Formulation of composites

WPC Code	BA Concentration (wt %)	Wood flour (wt %)	Polypropylene (wt %)	MAPP (wt %)
UT-WPC	0	40	58	*2*
BA-T-WPC	1 in powder	39	58	2
BA-PT-WPC	1 in solution	40	58	2

UT-WPC: untreated poplar wood flour/plastic composite; BA-T-WPC: boric acid treated poplar wood flour in manufacturing process/plastic composite; BA-PT-WPC: boric acid pretreated poplar wood flour/plastic composite; MAPP: maleic anhydride polypropylene.

2.3 Pretreatment and processing

For BA-PT-WPC, the poplar wood flour was immersed in a 1 wt% boric acid solution for 24 hours at room temperature. The soaked flour was then dried in an oven at 103 ± 2 °C until constant weight was achieved.

For BA-T-WPC, boric acid powder (1 wt%) was directly added to the blend during compounding without prior treatment of the wood flour.

All formulations were mixed using a twin-screw extruder operating at 160-180 °C with a screw speed of 60 rpm. The compounded materials were then pelletized and molded into standard test specimens by compression molding at 180 °C under 5 MPa pressure for 10 minutes, followed by cooling under pressure.

2.4 Decay resistance test

To evaluate biological durability, half of the test specimens were exposed to decay using the agar-block test method (ASTM D1413), with *Trametes versicolor* (white-rot fungus) as the degrading agent. Samples were incubated for 14 weeks at 23 ± 2 °C and 75% relative humidity (Figure 1).

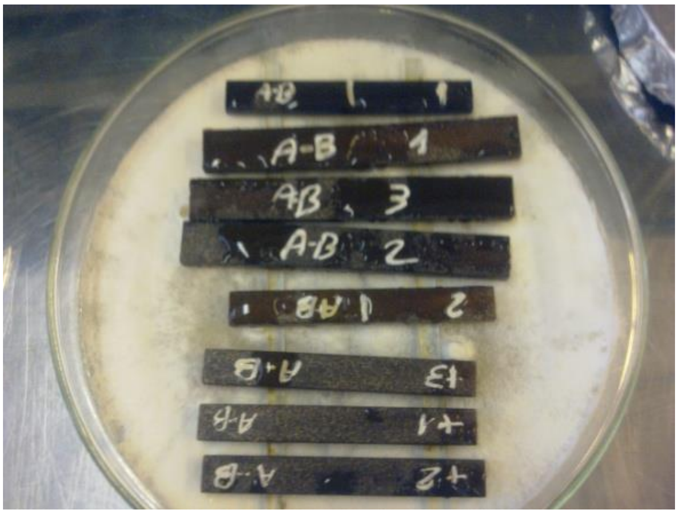

Figure 1. A typically of several BA-T-WPC and BA-PT-WPC samples exposed to white-rot fungus using the agar-block test method

2.5 Mechanical testing

Mechanical properties of both decayed and undecayed samples were measured as follows: Flexural strength and modulus – ASTM D790; Tensile strength and modulus – ASTM D638; Hardness – ASTM D2240 (Shore D); Impact strength – ASTM D256 (Izod method).

All tests were conducted on four replicates (N = 4) for each group. Statistical analysis was performed using SPSS software version (17 version]), and results are presented as mean ± standard deviation.

2.6 Water uptake and dimensional stability tests

Water uptake and thickness swelling tests of the composites were conducted by following the ASTM D 570 (1998) standard. Five specimens from each formulation were selected and oven-dried for 24 h at 100 ± 3 °C. The samples were weighted with an accuracy of 0.001 g after drying in the oven and their thicknesses were measured at an accuracy of 0.001 mm. Then, the specimens were placed in distilled water for 24 h by the method of immersion and retained at room temperature (20 ± 2 ºC). In the final of this time, the excess on the surface of the specimen was cleared with a clean cloth and then their weights and thicknesses were determined.

2.7 Fungus culture

The white-rot fungus (*T. versicolor*) was transferred to petri dishes containing malt extract agar (48 g/L) under laminar hood using sterile pincers. The plates were kept at 23 ºC for one week until the culture medium was fully covered by the mycelium of the fungus. The cultured fungus was transferred into petri dishes containing the culture medium and then incubated for one week at 23 ºC.

2.8 Inoculation of samples by fungus

Inoculation of composite samples by the fungus was performed in the petri dishes. The dishes containing the fungus and the composite samples were incubated in an incubator for 14 weeks at 23 ºC and 75% RH. The sizes of control WPCs samples are shown in the Figure 2.

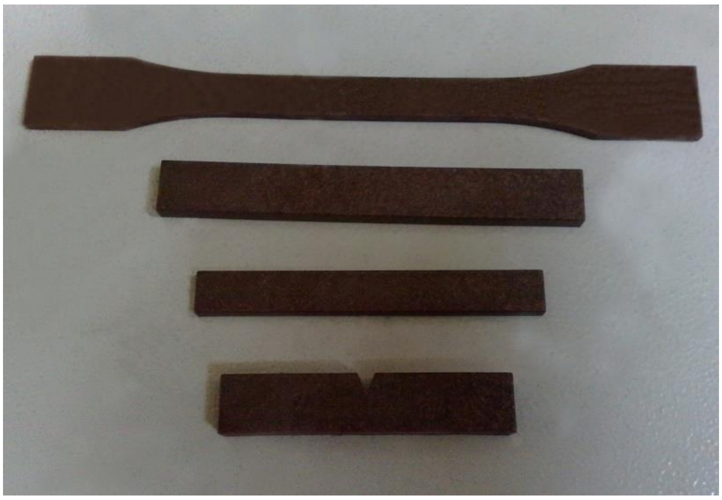

Figure 2. The sizes of WPCs control samples

2.9 Data analysis

Mass loss, flexural strength, flexural modulus, tensile strength, tensile modulus, impact strength, water absorption, and thickness swelling values were evaluated using a computerized SPSS 17.0 statistical program and tested with ANOVA followed by Duncan's Multiple Range Test (DMRT) with 95% confidence level.

3 Results and discussion

3.1 Weight loss

Figure 3 illustrates the weight loss of different wood-plastic composite (WPC) samples after exposure to the white-rot fungus *Trametes versicolor*. According to the data, the UT-WPC sample exhibited the highest weight loss, approximately 0.68%, indicating its low resistance to fungal decay. The BA-T-WPC sample, which was treated with boric acid during the mixing stage, showed a moderate reduction in weight loss about 0.35% demonstrating improved fungal resistance. The BA-PT-WPC sample, where wood flour was pretreated with a boric acid solution before composite processing, had the lowest weight loss at approximately 0.25%. These results reveal that boric acid treatment enhances the durability of WPCs against fungal attack. Specifically, pre-treatment of the wood flour (BA-PT-WPC) reduced weight loss by nearly 63% compared to the untreated control, and by 48% compared to in-process treatment (BA-T-WPC). According to the results of the Duncan test, no statistically significant differences were found between the groups. Although the graph suggests that the application of boric acid and its usage through different methods may have some slight effect. This strategy could be highly beneficial for extending the service life of wood-plastic composites in environments prone to fungal exposure.

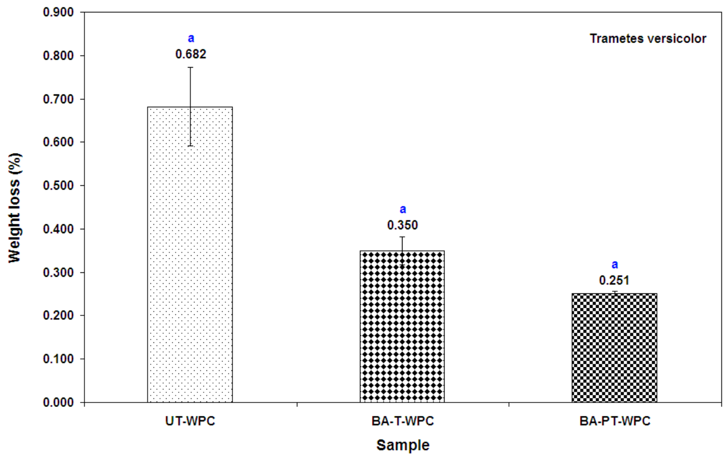

Figure 3. Effect of boric acid treatment on weight loss of wood flour/polypropylene composites (Duncan's multiple range tests are given in the graph)

The results of an investigation by Cavdar et al., (2018) on the effect of boron compounds (spruce wood flour was treated with boric acid (BA), borax (BX), and a BA-BX mixture, then incorporated into a polymer matrix at 20% and 40% loading rates) on the decay resistance and weight loss (brown-rot fungus, *Coniophora puteana* and white-rot fungus, *Trametes versicolor*) of wood-plastic composites (WPCs) indicated that boron-treated composites exhibited higher weight loss and moisture content compared to controls during decay tests. Notably, composites with higher wood flour content showed increased susceptibility to fungal decay, emphasizing the need for optimized treatment methods to enhance durability.

3.2 Hardness

The hardness of both UT-WPC and BA-PT-WPC samples decreased after exposure to fungal attack, except for the BA-T-WPC specimens. The results of Duncan's test indicated that the BA treatment had significant effect on the hardness of wood flour/polypropylene composites. In addition, there were significant differences between hardness values of BA-PT-WPC and BA-T-WPC undecayed samples (P<0.05). As can be seen in Figure 4, in comparison to UT-WPC (70.25 Shore D) the minor decrease (70.16 Shore D) and slight increase (71.22 Shore D) found in the hardness values of BA-T and BA-pretreated undecayed samples may be due to the precipitation of BA in the cell lumens and the cell wall of wood particles and the subsequent increase in density. It appears that in the BA-T-WPC samples, boric acid have precipitated on the surface and did not penetrate into the cell lumen or cell wall, but in the BA-PT-WPC, boric acid have precipitated in the cell cavity and the cell wall (Winandy and Rowell, 1984; Hosseini Hashemi et al., 2010; Badritala et al., 2013). After exposure to decay fungus, there were no significant differences between hardness values of BA-PT-WPC and BA-T-WPC decayed samples (P<0.05). Ünal et al., (2023) incorporated boric acid into polypropylene (PP) and wood flour composites and showed that while boric acid significantly enhanced, it caused a slight reduction in tensile strength. This decrease was attributed to the interference of boric acid with the bonding between the wood particles and polymer matrix, which negatively impacted interfacial adhesion.

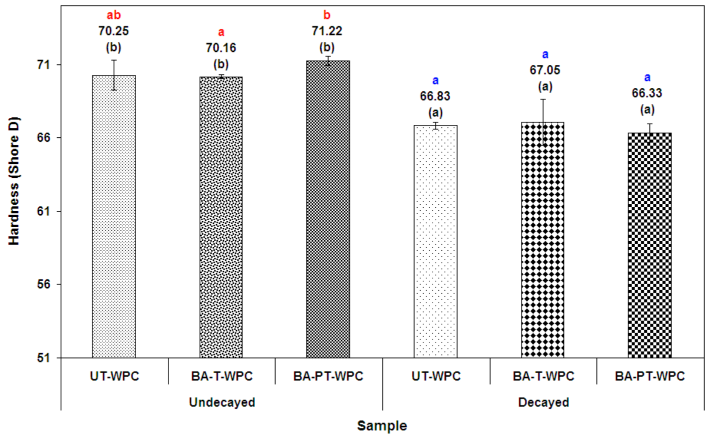

Figure 4. Effect of boric acid treatment on hardness of wood flour/polypropylene composites (Duncan's multiple range tests are given in the parentheses)

3.3 Impact strength

The results of Duncan's test indicated that the BA treatment had no significant effect on the impact strength of the composites before and after exposure to fungal attack, except for the BA-PT-WPC specimens (Figure 5). There were significant differences between BA-PT-WPC and BA-T-WPC undecayed and decayed samples (P<0.05). As can be seen in Figure 5, the specimens containing the BA-T and BA-PT showed lower and higher notched impact strength compared with the untreated specimens, respectively. The impact resistance of the BA-T-WPC and BA-PT-WPC specimens decreased by 14.7% and increased 7.2%, respectively, compared to the UT-WPC specimens. This was mainly attributed to the poor and rich compatibility between the BA-T and BA-PT wood and polymer matrix due to the crystalline deposits of boric acid, respectively (Ayrilmis et al., 2012). Also, the BA-PT-WPC specimens exhibited marginally greater average impact resistance compared to the BA-T-WPC ones. We expected that the BA treatment is probably affected on dispersion and precipitation of BA particles in the cavities of composites. This result can be attributed to the formation of agglomeration cause to reduction of adhesion in the composite interface compared with the BA-PT specimens. After exposure to decay fungus, there were significant differences between impact strength values of BA-T-WPC and BA-PT-WPC decayed samples (P<0.05).

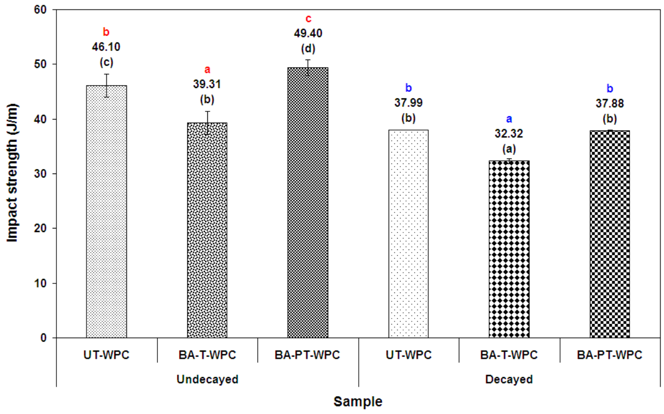

Figure 5. Effect of boric acid treatment on impact strength of wood flour/polypropylene composites (Duncan's multiple range tests are given in the parentheses)

Generally, it has been observed that boric acid, while beneficial for improving decay resistance, tends to reduce the impact strength of WPCs. This reduction is often attributed to the interference of boric acid with the interfacial bonding between the wood fibers and the polymer matrix, which weakens the load transfer during impact loading. For instance, Baysal et al., (2007) reported a moderate decrease in impact resistance when boric acid was incorporated, due to reduced compatibility between the components. Similarly, Ünal et al., (2023) investigated the mechanical properties of polypropylene (PP) composites filled with varying weight percentages (5%, 10%, and 15%) of boric acid (BA).They found that tensile strength and modulus decreased with increasing BA content.Impact strength increased slightly at 5% BA content but decreased at higher concentrations.These findings suggest that while low concentrations of boric acid can enhance certain mechanical properties, higher concentrations may have adverse effects.

3.4 Flexural strength and modulus

The results of Duncan's test indicated that the BA treatment had significant effect on the flexural strength of undecayed samples, but had no significant effect on the flexural strength of decayed samples. However, there was a significant differences between the flexural modulus values of the BA-T-WPC and BA-PT-WPC (P<0.05) in undecayed samples. As can be seen in Figures 6 and 7, the flexural strength and modulus of BA-PT-WPC and BA-T-WPC specimens were higher than the corresponding untreated specimens, except for the flexural modulus of BA-PT-WPC specimens. This is probably due to the increase in stiffness caused by formation of BA crystalline deposits in cell lumen of wood flour. This finding is consistent with those of previous studies (Ayrilmis et al., 2011; Ayrilmis et al., 2012; Kurt and Mengeloglu, 2011). Also, the BA-T-WPC specimens had higher flexural strength and modulus than the BA-PT-WPC ones. It seems that the specimens containing the BA-PT due to the formation of agglomeration cause to reduction of adhesion in the composite interface compared with the BA-T specimens. After exposure to decay fungus, there were no significant differences between flexural strength and modulus values of BA-T-WPC, BA-PT-WPC, and UT-WPC decayed samples (P<0.05).

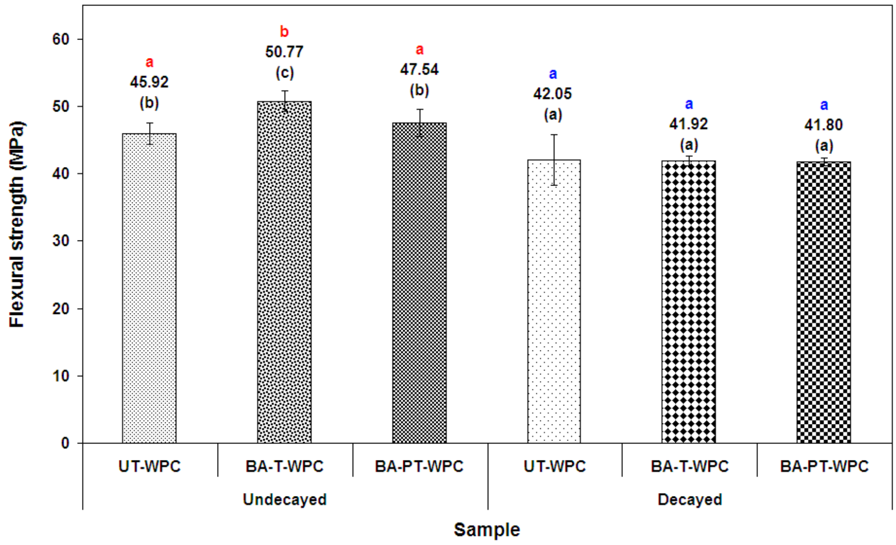

Figure 6. Effect of boric acid treatment on flexural strength of wood flour/polypropylene composites (Duncan's multiple range tests are given in the parentheses)

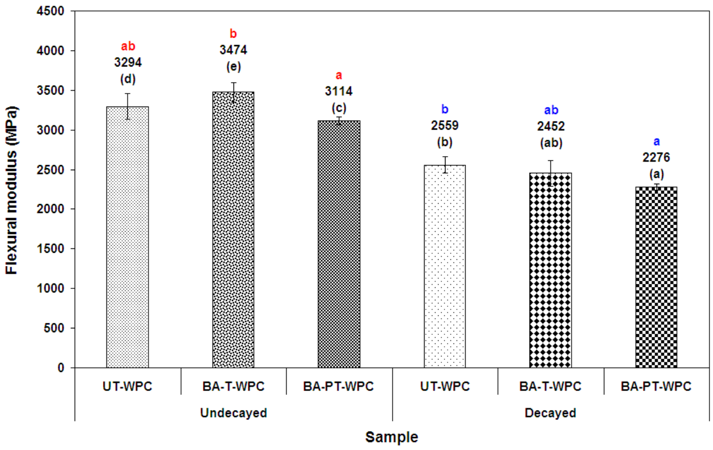

Figure 7. Effect of boric acid treatment on flexural modulus of wood flour/polypropylene composites (Duncan's multiple range tests are given in the parentheses)

The results of a study conducted by Baysal et al., (2007) on the effects of boric acid (BA) and borax (BX) pretreatment on the mechanical properties of wood-plastic composites indicated an increase in modulus of elasticity (MOE) and modulus of rupture (MOR) compared to untreated controls. Furthermore, the BA/BX treatment significantly enhanced the composites' resistance to fungal decay and improved their fire retardancy. These findings suggest that boron compounds can be beneficial in improving both the mechanical performance and durability of wood-plastic composites.

3.5 Tensile strength and modulus

The results of Duncan's test indicated that BA treatment had no significant effect on the tensile strength and modulus of the BA-treated WPC specimens ($P \geq 0.05$). Also, there were no significant differences between tensile strength and modulus values of UT-WPC, BA-T-WPC, and BA-PT-WPC. As can be seen in Figures 8 and 9, the tensile strength and modulus of BA-T-WPC and BA-PT-WPC specimens were higher than for the untreated specimens. Also, the

BA-T-WPC specimens had higher flexural strength than the BA-PT-WPC ones, but the BA-T-WPC specimens had lower flexural modulus than the BA-PT-WPC ones. The reduction of tensile strength and modulus in the BA-treated composites can be attributed to the same reasons as discussed concerning flexural strength and modulus.

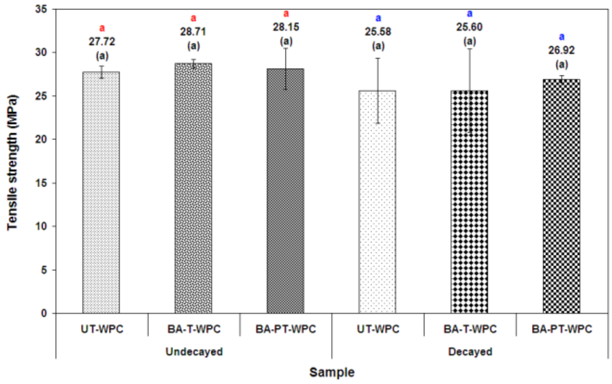

Figure 8. Effect of boric acid treatment on tensile strength of wood flour/polypropylene composites (Duncan's multiple range tests are given in the parentheses)

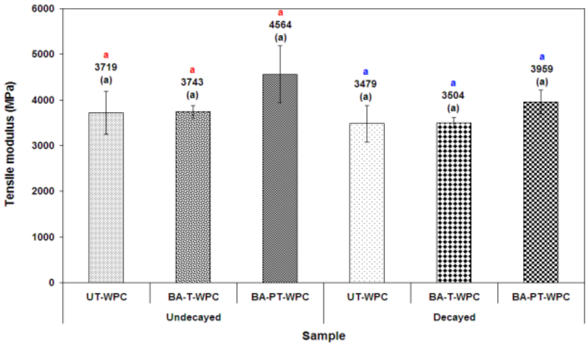

Figure 9. Effect of boric acid treatment on tensile modulus of wood flour/polypropylene composites (Duncan's multiple range tests are given in the parentheses)

The results of other researcher indicated that although boric acid significantly improved the flame retardancy of the composites, it caused a slight decrease in tensile strength. This reduction was attributed to the weakened interfacial bonding between the wood particles and the polymer matrix due to the presence of boric acid (Ünal et al., 2023). Tensile strength of glass fiber-reinforced epoxy composite plates by adding boric acid to the epoxy in different ratios (0, 0.5, 1, and 1.5% by weight) revealed that the highest tensile strength was obtained from the 0.5% BA-added specimens, with a 24.78% increase compared to the 0% BA-added specimens. However, as the BA ratio increased beyond 0.5%, the tensile strength decreased. The study concluded that while a 0.5% addition of boric acid improved the tensile strength, higher concentrations led to a reduction in mechanical properties due to interlayer delamination and fiber/matrix failure (Örçen and Bayram, 2024).

It should be noted that in Figures 4-9, different letters in red and blue colors indicate significance at the 5% level within undecayed and decayed samples separately, while different letters in black color inside parentheses indicate significance at the 5% level for comparisons between undecayed and decayed samples.

3.6 Water and thickness swelling resistance

The results of statistical analysis (Table 2) indicated that pretreating wood flour with a 1% boric acid solution (BA-PT-WPC) enhances long-term water resistance, particularly under decay conditions. This improvement is likely due to better interfacial bonding and reduced fungal degradation pathways. In contrast, incorporating boric acid during blending (BA-T-WPC) shows limited effectiveness over prolonged exposure. These findings align with those of Baysal et al., (2007), who reported that pretreating wood with a boric acid and borax mixture before polymerization improved water resistance and decay durability of WPCs. The study found that such pretreatment reduced water absorption and enhanced resistance against decay fungi, supporting the notion that pretreatment methods are crucial for long-term performance. However, other studies present differing perspectives. For instance, Kartal et al., (2007) observed that wood specimens treated with boron compounds followed by heat modification exhibited increased water absorption due to the hygroscopic nature of boric acid. This suggests that while boric acid can enhance certain properties, its hygroscopicity may counteract benefits in water resistance under specific conditions. Additionally, Zhang et al., (2021) investigated borated wood-polycarbonate biocomposites and found that while boric acid improved fire retardancy, it also led to increased water absorption. The study attributed this to the hydrophilic nature of lignocellulosic fibers, which absorb moisture and potentially weaken the fiber-polymer interface. These contrasting findings highlight the complexity of boric acid's role in WPCs. While pretreatment methods like BA-PT-WPC can enhance long-term water resistance, factors such as the hygroscopic nature of boric acid and the type of polymer matrix used can influence outcomes. Therefore, optimizing treatment methods and considering the specific application environment are essential for achieving desired performance in WPCs.

Table 2. Water absorption (WA) of the untreated and treated composites

Decayed WPC	Time (h)	Mean ± Std. Deviation	Undecayed WPC	Time (h)	Mean ± Std. Deviation
UT-WPC	2	0.43 ab* ± (0.25)	UT-WPC	2	1.39 e ± (0.15)
BA-T-WPC	2	0.35 a ± (0.01)	BA-T-WPC	2	1.30 e ± (0.08)
BA-PT-WPC	2	0.57 b ± (0.04)	BA-PT-WPC	2	1.21 de ± (0.03)
UT-WPC	24	0.98 c ± (0.03)	UT-WPC	24	2.27 g ± (0.12)
BA-T-WPC	24	1.02 cd ± (0.03)	BA-T-WPC	24	2.15 g ± (0.04)
BA-PT-WPC	24	0.97 c ± (0.04)	BA-PT-WPC	24	1.89 f ± (0.04)
UT-WPC	1000	3.67 h ± (0.15)	UT-WPC	1000	6.26 k ± (0.38)
BA-T-WPC	1000	4.31 i ± (0.11)	BA-T-WPC	1000	6.21 k ± (0.27)
BA-PT-WPC	1000	3.60 h ± (0.07)	BA-PT-WPC	1000	5.48 j ± (0.03)

* Different letters in each column indicate a statistical difference ($p < 0.05$) among the composite groups. Values in parentheses are standard deviation (SD).

The results of statistical analysis (Table 3) indicated that in decayed samples, BA-T-WPC exhibited the lowest thickness sweling (TS) (0.00% ± 0.00), indicating a strong protective effect against moisture uptake due to fungal degradation. In contrast, BA-PT-WPC showed the highest TS (0.43% ± 0.25), possibly due to increased surface area or microvoids caused by dual treatment. For undecayed samples, BA-T-WPC recorded the highest TS (5.09% ± 0.75), while BA-PT-WPC showed relatively lower TS (3.02% ± 0.45) than even UT-WPC (3.39% ± 0.44), suggesting that treatment during manufacture may decrease short-term dimensional stability under non-biological conditions. After 24 hours, TS increased in all samples. In decayed composites, both BA-T-WPC and BA-PT-WPC exhibited higher TS values (3.31% ± 1.00 and 3.64% ± 0.38, respectively) compared to UT-WPC (1.86% ± 0.82), implying that boric acid treatments may increase water affinity or fail to fully protect against degradation-induced moisture penetration. In undecayed samples, however, BA-PT-WPC maintained the lowest TS (3.28% ± 0.55), reinforcing its efficacy under intact, fungal-free conditions. In the long-term immersion test, all samples exhibited a significant increase in TS. BA-T-WPC (4.79% ± 0.55) and BA-PT-WPC (4.76% ± 0.63) showed marginally higher TS than UT-WPC (3.06% ± 0.20) in decayed samples, indicating the limited durability of treatments when subjected to prolonged fungal and moisture exposure. In undecayed WPCs, BA-T-WPC displayed the highest TS (7.24% ± 0.60), followed by BA-PT-WPC (6.30% ± 1.18) and UT-WPC (5.43% ± 0.34), suggesting that boric acid treatments may become less effective over extended periods. Matuana et al., (1998) reported that while chemical modifications can improve short-term water resistance, the benefits often diminish over time, particularly under prolonged exposure to water and fungi. Stark and Berger (1997) demonstrated that untreated WPCs often exhibit less swelling than treated counterparts in the long term, due to degradation of additives or leaching of treatment agents. Clemons (2002) emphasized that preservative treatments may initially improve water repellency, but long-term thickness swelling still occurs due to capillary water uptake through interfacial gaps and surface degradation. Overall, preservative treatments (especially BA-PT) show promise for improving short-term water resistance in WPCs, particularly under non-decay conditions. However, long-term exposure and fungal decay significantly reduce their effectiveness, leading to increased thickness swelling. These results highlight the need for more durable and moisture-resistant treatment systems for WPCs, especially for applications in humid or biologically active environments.

Table 3. Thickness swelling (TS) of the untreated and treated composites

Decayed WPC	Time (h)	Mean ± Std. Deviation	Undecayed WPC	Time (h)	Mean ± Std. Deviation
UT-WPC	2	0.17 a*± (0.12)	UT-WPC	2	3.39 c ± (0.44)
BA-T-WPC	2	0.00 a ± (0.00)	BA-T-WPC	2	5.09 e ± (0.75)
BA-PT-WPC	2	0.43 a ± (0.25)	BA-PT-WPC	2	3.02 c ± (0.45)
UT-WPC	24	1.86 b ± (0.82)	UT-WPC	24	3.90 cd ± (0.37)
BA-T-WPC	24	3.31 c ± (1.00)	BA-T-WPC	24	5.17e ± (0.77)
BA-PT-WPC	24	3.64 c ± (0.38)	BA-PT-WPC	24	3.28 c ± (0.55)
UT-WPC	1000	3.06 c ± (0.20)	UT-WPC	1000	5.43 e ± (0.34)
BA-T-WPC	1000	4.79 de ± (0.55)	BA-T-WPC	1000	7.24 g ± (0.60)
BA-PT-WPC	1000	4.76 de ± (0.63)	BA-PT-WPC	1000	6.30 f ± (1.18)

*Different letters in each column indicate a statistical difference ($p < 0.05$) among the composite groups. Values in parentheses are standard deviation (SD).

3.7 Scanning electron microscope analysis for decayed and undecayed WPC samples

The SEM micrographs illustrate the surface morphology of six different decayed and undecayed wood-plastic composite (WPC) samples (Figure 10). The Figures 10a, 10b, and 10c (top, left to right) shows decayed samples, while the Figures 10d, 10e, and 10f (bottom, left to right) shows undecayed ones. The decayed untreated WPC (UT-WPC) (10a) exhibits severe degradation, with visible cracks, voids, and disrupted fiber-matrix bonding, indicating high susceptibility to biological decay. The decayed BA-treated WPC (BA-T-WPC) (10b) shows moderate degradation, suggesting that BA-treatment improved resistance but was not entirely effective. The decayed BA-pre-treated WPC (BA-PT-WPC) (10c) presents the least damage, retaining a relatively intact and compact structure, confirming the effectiveness of full treatment in enhancing decay resistance. In contrast, the undecayed samples demonstrate significantly better structural integrity. The untreated WPC (UT-WPC) (10d) already shows some surface roughness and porosity, while the BA-treated (BA-T-WPC) (10e) and BA-pre-treated WPC (BA-PT-WPC) (10f) show progressively smoother and denser morphologies, indicating improved compatibility and bonding between wood fibers and polymer matrix due to the BA-treatment processes. These observations confirm that BA-treatments enhance the durability and microstructural stability of WPCs, especially under decay fungus.

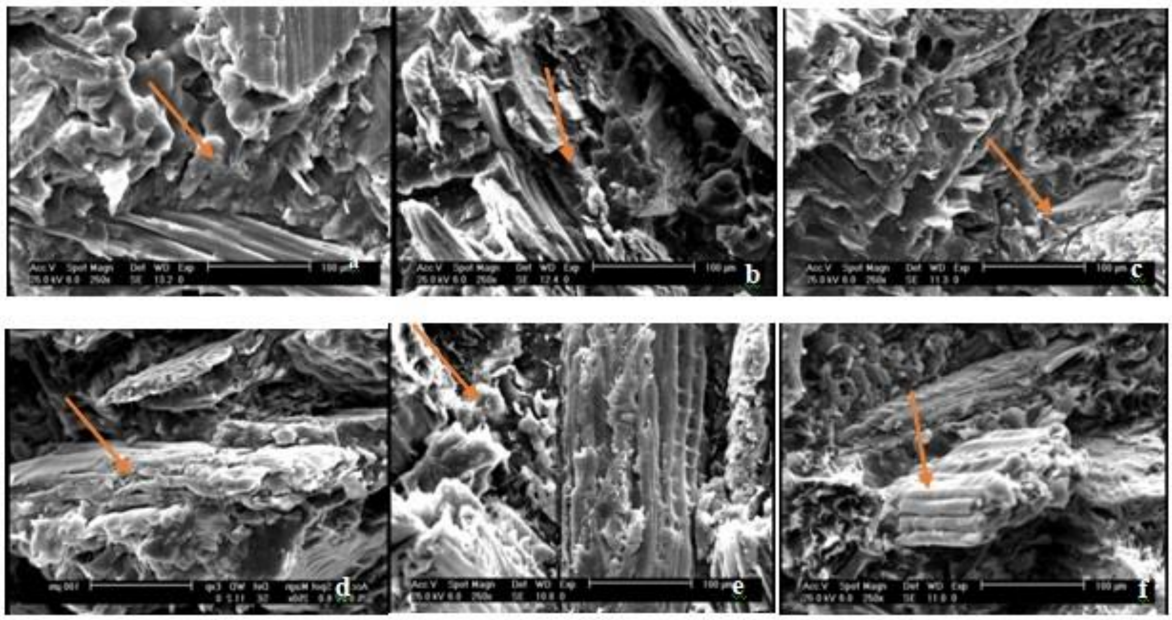

Figure 10. SEM micrographs of surface fracture of weight loss (decayed) and tensile (undecayed) samples with 100 μm magnifications. (a), denote the decayed UT-WPC; (b), denote the decayed BA-T-WPC; (c), denote the decayed BA-PT-WPC. (d), denote the undecayed UT-WPC; (e), denote the undecayed BA-T-WPC; (f), denote the udecayed BA-PT-WPC.

4 Conclusions

- This study demonstrates that boric acid treatment can significantly enhance the mechanical properties and decay resistance of wood flour/polypropylene composites. Both in-process powder addition and aqueous pre-treatment methods improved the composites' strength and durability, with BA-treated specimens showing better performance after fungal exposure.
- BA-T-WPC exhibited the highest flexural strength (50.77 MPa) and modulus (3473 MPa), while BA-PT-WPC demonstrated superior tensile modulus (4563 MPa) and impact strength (49.40 J/m).
- SEM images show that boric acid deposits on wood fibers increase surface area but may weaken polymer bonding. Fiber pull-out and holes indicate poor fiber-matrix adhesion, especially in pre-treated composites. Overall, boric acid treatment presents a promising approach to develop more durable and mechanically robust WPCs for wood-plastic applications.

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Author Contributions
Seyyed Khalil HosseiniHashemi: Creating the research idea, writing the article, performing the statistical operations, **Alireza Badritala**: conducting the laboratory work, taking the measurement data, **Maliheh Akhtari:** Analysis and interpretation of data, writing the article.

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Conflict of interest
We confirm that there is no conflict of interest.

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