European Journal of Wood and Wood Products
https://doi.org/10.1007/s00107-023-01993-w

ORIGINAL ARTICLE

Formulation and characterization of environmentally benign chicken feather-based wood preservatives

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Received: 16 March 2023 / Accepted: 11 September 2023

Abstract
This paper develops chicken feather protein-based wood preservatives (CFP-WP). The treatability, leachability and chemical structure of the CFP-WP were analyzed. The crystallinity, thermal properties, micromorphology and decay resistance against fungi of the treated wood samples were investigated to examine their efficacy. The production cost of CFP-WP was also assessed. The results showed that CFP-WP (Cu, B and small molecular amino acids) was able to penetrate into wood cell walls and the active ingredients of preservatives interacted with wood constituents were well fixed onto wood blocks, evidenced by SEM–EDS observation, NMR, FTIR, XRD and TGA/DTG analysis. The morphology analysis elucidated that CFP-WP effectively protected wood against decay fungi. Decay experiments verified that the new preservative prolonged the wood service life, reducing the mass loss up to 10.88% from 51.02% compared to the untreated wood. Further, the production cost of CFP-WP (approx. 130–140 €/tonne) is nearly 30% lower than the commercial price of conventional market preservatives, such as ACQ (approx. 210 €/tonne). The excellent functionalities of this CFP-WP eco-friendly formulation present a great potential to be used as an environmentally benign wood preservative.

1 Introduction

Wood is one of the most attractive renewable resources contributing to the global bio-based economy development. However, wood is susceptible to deterioration caused by microorganisms and/or insects, and inevitably needs to be preservative-treated. Unfortunately, most traditional preservatives have serious environmental and human health concerns about toxic chemicals, and hence some traditional wood preservatives, such as chromate copper arsenate (CCA), are limited to nonresidential uses (Thevenon et al. 2009; Can et al. 2018; Chu et al. 2019). As a consequence, it is urgent to develop effective, environmentally friendly and cost-competitive alternatives (Lyon et al. 2007; Ljunggren et al. 2020; Woźniak et al. 2022). Bio-based or bio-friendly wood preservatives developed from natural sources, which could efficiently improve the durability of woody materials against microorganisms, endow great potentials in replacing traditional wood preservatives and attract increasing interest from industries and researchers attributing to the environmentally friendly concept and its new preservative system (Anttila et al. 2013; Broda et al. 2020; Barbero-López et al. 2021).

Chicken feathers, mostly disposed as waste, are cheap, environmentally friendly, rich in source and high in protein content (90%) (Taskin 2013; Song et al. 2014). Chicken feathers could be hydrolyzed into small molecule amino acids (Taskin 2013), in which valine is the most abundant amino acid followed by glutamic acid. Amino acids can chelate with insoluble salt elements to form a chelate with good solubility and absorption (Taskin 2013; Junxiang et al. 2015; Shuai et al. 2017). Though chicken feathers have been utilized in many fields as a natural resource, research on new preservatives formulated by chicken feathers with functional salts is yet to be explored.

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Published online: 29 September 2023

Copper salts, which are poisonous to microorganisms and insects, have been used most commonly in wood preservatives (Ribera et al. 2017; Shukla and Kamdem 2022). Boron salts are the oldest preservatives and still used as effective fungicides and insecticides nowadays on account of their low toxicity (Kartal et al. 2022). Copper and boron salts attracted increasing attention as antifungal salts due to their excellent antifungal efficacy and low toxicity. However, the leakage of copper and boron salts from the treated wood products during application is inevitable due to their water solubility (Kim et al. 2011; Liu et al. 2018; Zhao et al. 2022). Thus, new preservative systems need to be developed to achieve the stabilization and fixation of copper and boron salts in wood structures (Yamaguchi and Yoshino 2001; Rodrigues et al. 2012). Protein has been attempted as a fixative agent of wood preservatives and several fixing agents have been tested in combination with antifungal salts to enhance their interaction through coagulation, such as tannin (Ratajczak et al. 2008), lignin (Hoffmann et al. 2008), animal blood (Mazela and Polus-Ratajczak 2003) and soy protein (Thevenon et al. 1997; Ahn et al. 2008; Kim et al. 2011). There is still a high need for exploring new protein sources with commercially competitive costs.

This study explores a new system of preservation utilizing chicken feathers, the residue of poultry processing, chelating with copper and boron salts. Chicken feathers may be developed as a natural source of protein and employed as a fixative agent in wood preservative formulations due to their great availability, high protein content and good solubility after chelating. The objectives are to (1) determine whether the hydrolyzed chicken feather protein could be developed in formulating a new eco-friendly preservative as an efficient fixative agent of wood preservatives with antifungal salts Cu and B, and examine the stability of the chicken feather protein-based wood preservatives (CFP-WP); (2) elucidate the CFP-WP working mechanisms, that is, whether and how the chicken feather-based preservative could penetrate into and effectively fix onto the wood cell walls; (3) evaluate the resistance efficacy of the treated wood against decay fungi and assess the cost of the new preservative. The study provides a new branch of preservative formulations from natural resources to replace traditional toxic CCA for wood protection and maintenance as well as a prospective approach to reduce the risk of environmental pollution. Socioeconomic benefit is also assessed.

2 Materials and methods

2.1 Preparation of the preservatives

The preservative formulations were developed with chicken feather protein (CFP) chelated with copper sulfate ($CuSO_4{\cdot}5H_2O$, Cu) and sodium borate ($Na_2B_4O_7{\cdot}10H_2O$, B). Chicken feathers were supplied by a chicken shop (Wuding Chicken Shop, China). Figure 1 and Table 1 show the preparation process and the formulations of CFP-WP.

Alkali hydrolysis was employed and the optimal hydrolysis process was determined according to the minimum residual solid content after hydrolysis. Chicken feathers were cleaned and immersed in sodium hydroxide solution (6 wt%) at room temperature for 24 h, then hydrolyzed at 140 °C for 4 h to obtain CFP aqueous solution.

The target retention of Cu for the protein-based preservative combined with copper and boron has been reported as 6–12 kg/m^3 or 8–40 kg/m^3 (Yang et al. 2006; Ahn et al. 2008). To examine the effectiveness of the developed protein-based preservative, the target retention of Cu in the study was set from 6 to 18 kg/m^3, and the boron from 10 to 20 kg/m^3 as shown in Table 1. The filtrated CFP aqueous solution was firstly added into the suspension of Cu and B (combined with Cu and B solutions), and to dissolve the water-insoluble mixture, ammonium hydroxide (NH_4OH) was added with a volume ratio of 10% into the suspension of Cu, B and protein, then the CFP-WP preservative aqueous solution was achieved. Three formulations of CFP-WP were prepared, i.e. P_1, P_2, and P_3 as listed in Table 1.

The representative species of *Pinus yunnanensis* (*P. yunnanensis*) was used to examine the efficacy of the developed CFP-WP due to its fast growth, wide plantation, and broad application. After the CFP-WP were formulated, the sapwood blocks sawed from *P. yunnanensis* with a size of 20 mm (cross-section) × 20 mm (radial-section) × 200 mm (longitudinal-section) without any defect were dipped in preservative formulations for 24 h at ambient condition, followed by oven-drying at 103 ± 3 °C for 24 h and air-drying over 24 h.

2.2 Treatability and leachability of the developed preservatives

To examine the actual preservative retention in the wood blocks, 5 g of treated wood powder were mixed with 50 ml sulfuric acid (2.5 mol/L) and 10 ml hydrogen peroxide (30% percent) in an Erlenmeyer flask, and the mixtures were oscillated in a water bath at 75 °C for 30 min, then the hydrolysates were collected. Treatability was calculated by the ratio of the measured retention of the treated samples to the target retention. Six treated wood blocks of each preservative

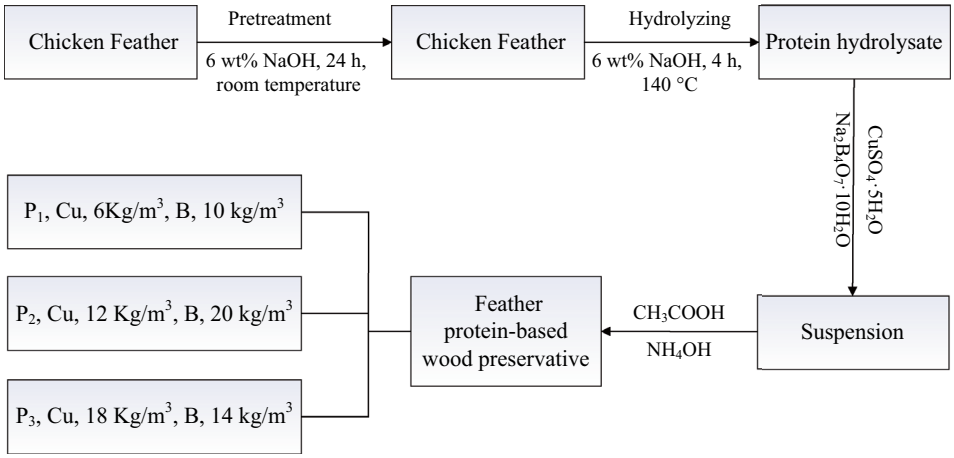

Fig. 1 The preparation process for the feather protein-based wood preservatives

Table 1 Formulations of feather protein-based wood preservatives

Formulations	Target-retention/Kg m^{-3}		Chicken feather hydrolyzate/ Kg m^{-3}
	Copper sulfate	Sodium borate	
P_1	6	10	16
P_2	12	20	32
P_3	18	14	32

formulation with the size of 20 mm (cross-section) × 20 mm (radial-section) × 10 mm (longitudinal-section) were subjected to water leaching test to evaluate the stability of active ingredients. The wood blocks were placed in 100 ml water at ambient temperature, and the extractive water was replaced with fresh water. The replacement interval time of the water was 6, 12, 24 and 48 h, then 48 h interval until 14 days, and all the leachates were collected. An inductively coupled plasma automatic emission spectrometer (ICP-AES) was utilized to analyze the Cu and B contents of the hydrolysates and the leachates according to the Chinese standard GB/T 29905-2013.

2.3 Chemical characterization, crystallinity and thermal stability

The preserved wood samples were pulverized into fine powder (40–60 mesh screen) to determine the chemical structures by the Fourier transform infrared (FTIR) analysis, and the Cu-B complex and CFP-WP were analyzed through FTIR as well after rotary steaming and freeze-drying. The FTIR spectra were measured on a Thermo Scientific Nicolet iN10 FTIR (Thermo Nicolet Corporation, USA) in the range from 4000 to 400 cm^{-1} with 32 scans per sample at a resolution of 4 cm^{-1}.

The crystallinities of the control and treated wood samples were measured by conducting X-ray diffraction (XRD) analysis (Shimadzu, Japan) using Ni-filtered CuKa radiation at 40 kV and 30 mA. The XRD pattern was recorded at 2θ of 5°–40° at a scanning rate of 0.4 s/step with a total of 2685 steps.

Thermal characteristic was measured by Thermo gravimetric analysis (TGA), conducted on DTG-60 (Shimadzu, Japan), a simultaneous thermal analyzer. Wood powder weighed 3–5 mg in an aluminum crucible was heated from room temperature to 600 °C at 10 °C·min^{-1} heating rate in a nitrogen atmosphere.

Solid-state ^{13}C NMR analysis was carried out to track the structural changes of the treated wood samples during preservative modification. ^{13}C NMR spectra were obtained using a Bruker AV-III 400 M spectrometer (Germany).

2.4 Observation of microscopic structure

Scanning Electron Microscope (SEM) and Energy Dispersive Spectrometer (EDS) techniques were performed to observe and illustrate the microstructure and chemical composition changes within the cell wall of the preservative treated wood samples. SEM–EDS analysis was performed at 10 kV and 81 mA with Hitachi S-3400 N II (Hitachi, Japan).

2.5 Decay resistance

The laboratory decay tests were carried out with 12 wood samples of each CFP-WP formulation, with the size of 20 mm (cross-section) × 20 mm (radial-section) × 10 mm (longitudinal-section) cut from the treated samples, and brown-rot fungus *Gloeophyllum trabeum* (*G. trabeum*) was applied to examine the decay resistance of wood against fungi.

According to the Chinese standard GB/T13942.1-2009, *G. trabeum* was incubated at 28 °C and 85% relative

humidity in the incubator until mycelium covered the entire surface of the agar. Then, the mycelium with a 1 cm diameter was transferred onto the surface of the feed strips (masson pine, 20 mm (cross-section) × 20 mm (radial-section) × 10 mm (longitudinal-section), supplied from a wood company (Gongxiang Wood Company, China)), onto which the sterilized wood samples will be transferred after mycelium covered the entire surface of the feed strips, totally 48 wood samples, 12 samples for each formulation including the control group. Two sterilized wood samples were settled on the feed strips in each bottle. These culture bottles were incubated for 12 weeks at 28 °C and 85% relative humidity. After the decay test, wood blocks were removed from bottles, cleaned off fungal mycelium, dried thoroughly at 103 ± 3 °C in the oven, and weighed to measure the mass loss. Wood decay resistance was represented by the average mass loss after exposure to decay fungi.

3 Results and discussion

3.1 Stability of the developed CFP-WP

The stability was examined by using the treatability and leachability of the treated wood blocks with the developed CFP-WP formulations (Table 2). Treatability stands for the actual preservative retention in the wood blocks and leachability represents the percentage content of the Cu and B in the leachates.

It can be seen in Table 2 that the measured treatability values were 78–89%, in which the deviations between the target and measured retentions might be due to the ambient condition of the treatment process without pressure, size of wood samples and loss of soluble wood materials during the impregnation process. Considering the protein is a large molecule and hard to permeate uniformly into wood blocks, the high treatability values suggested that CFP could be hydrolyzed into low molecules and then penetrate into the wood structure by the dissociating agent ammonium hydroxide accordingly.

Among the three formulations, although the measured Cu retention of P_3 was the highest, P_2 could prospectively be the preferably appropriate environmentally benign formulation among the three preservative formulations due to its lower Cu content and higher B content compared to P_3 formulation, and could provide more sufficient protection to wood blocks attributed to the higher retained of B content after the leaching test.

3.2 Chemical structure of CFP-WP

3.2.1 FTIR analysis of CFP-WP and its treated wood

It can be seen that after being combined with chicken feather protein, the peaks of the Cu-B complex at 1120 cm^{-1} and 870 cm^{-1} (Fig. 2), corresponded to B-O stretching vibrations, and at 770 cm^{-1} to B-O-B bending vibrations (Issever et al. 2021) disappeared. Besides, the absorption bands at 980 cm^{-1} and 940 cm^{-1} (Cu–O stretching vibrations) shifted to 920 cm^{-1}. Compared with the Cu-B complex, the peaks at 1690 cm^{-1} and 1550 cm^{-1} (–Cu–N–B) and the peak at 1240 cm^{-1} (C=O of acid amides) proved that the hydrolyzed protein chelated with Cu and B in CFP-WP (Xia 2007; Ye 2015). The completely different spectral characteristic between CFP-WP and Cu-B complexes suggested that CFP-WP is a distinct compound compared to the Cu-B complex.

As can be seen from Fig. 3, the bands at 3400 cm^{-1} and 2926 cm^{-1} declined, revealing that the hydroxy and aliphatic acid extractives of wood might react with the active ingredients, Cu and B of CFP-WP, during the modification process. Significant shift even disappearance of the peaks of treated samples occurred at 1735 cm^{-1}, assigned to the acetyl group, indicating the modification of hemicellulose during preservative impregnation, especially the samples treated by P_2 and P_3 (Liu et al. 2019). The absorption bands at 1650 cm^{-1} and 1590 cm^{-1} of the samples treated by P_2 and P_3 shifted to 1580 cm^{-1} and even disappeared at 1505 cm^{-1}, assigned to the aromatic skeleton, suggesting the modification of lignin. Moreover, the peaks at 1370 cm^{-1} and 1040 cm^{-1} corresponding to cellulose also diminished, implying the interaction occurred between cellulose and CFP-WP. There

Table 2 Treatability and leachability of the feather protein-based wood preservatives

Formulations	Active agent	Target retention (kg m^{-3})	Measured retention (kg m^{-3})	Treatability (%)	Leaching contents (kg m^{-3})	Leachability (%)
P_1	Cu	6	4.705	78.42	1.083	23.02
	B	10	8.307	83.07	2.149	25.87
P_2	Cu	12	10.290	85.75	2.405	23.37
	B	20	17.872	89.36	5.231	29.27
P_3	Cu	18	14.856	82.53	4.010	26.99
	B	14	11.890	84.93	3.480	29.27

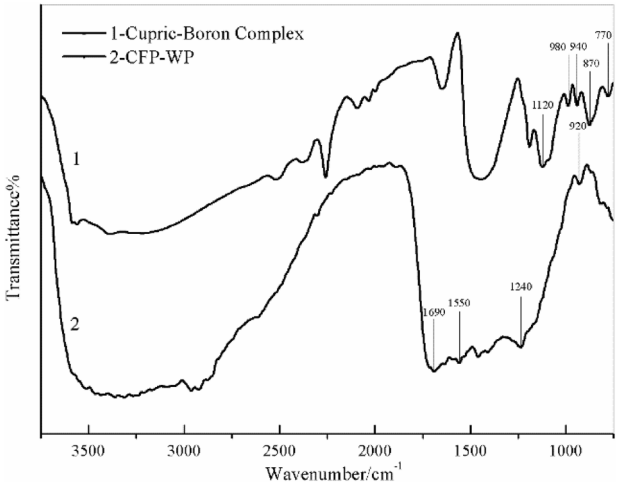

Fig. 2 FTIR spectra of CFP-WP

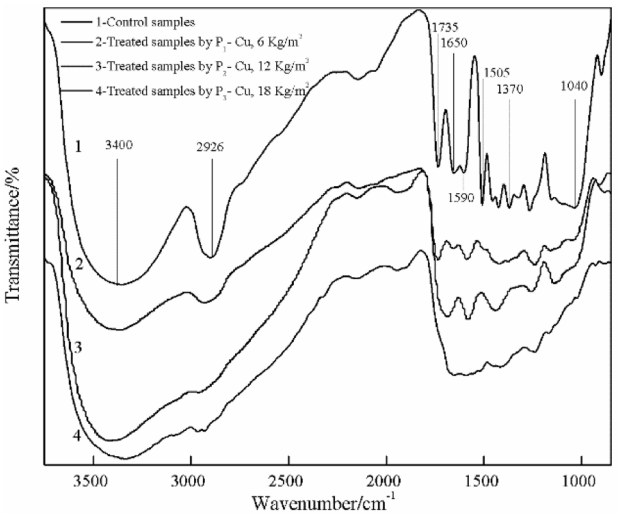

Fig. 3 FTIR spectra of wood samples

was a literature stating that soluble copper salts could react with lignin and bind in the wood matrix but with insufficient amounts (Yang et al. 2006). Compared with lignin, boron salts preferred to react with polysaccharides, but seemed to be physical adsorption and not chemical adsorption, which was easily leached (Ramos et al. 2006). Protein could chelate copper salts and boron salts with some of the -NH-CO- groups and react with wood components, then fix copper and boron salts to the wood matrix by the gelation of protein (Ratajczak and Mazela 2007). Therefore, it can be inferred that except a partial amount of copper reacts with lignin and partial boron reacts with polysaccharides, CFP-WP could fix onto wood matrix due to the protein reaction with wood components (Terzi et al. 2016; Basile et al. 2018; Xia et al. 2020).

Interestingly, the changes in the intensity of functional groups due to the interaction between wood components and CFP-WP were more remarkable with the increase of Cu and B contents of CFP-WP. These obvious changes in the chemical structures of the treated blocks suggested that the modification of wood constituents occurred after the preservative treatment, concluding that CFP-WP was an effective system for wood protection being able to permeate into wood blocks and efficiently react with wood components.

3.2.2 NMR spectral analysis of the CFP-WP treated wood

To obtain the detailed structural characteristic of the wood before and after preservative modification, the wood samples were characterized by the solid-state ^{13}C NMR. In Fig. 4, the signals of control sample predominantly appeared at 103.8 ppm (cellulose/xylan C-1), 87.9 ppm (crystalline cellulose C-4), 82.5 ppm (amorphous cellulose/xylan C-4), 71.8 ppm (celluloseC-2/3/5; xylanC-2/3), 63.0 ppm (crystalline cellulose C-6) and 60.9 ppm (amorphous cellulose C-6/xylan C-5). Moreover, 54.9 ppm was originated from the methoxyl of lignin and 20.8 ppm was related to the acetyl groups on hemicelluloses (Wen et al. 2010, 2013; Sun et al. 2021). It can be seen significant signals occurred at 32.9 and 30.3 ppm of the P_2 group, which did not belong to the units of cellulose, hemicellulose or lignin. These two signals should result from the predominant nature of the protein and the amino-acid residues, especially the valine (Lorch et al. 2005; Renault et al. 2013; Wiegand et al. 2017). Since valine was the most abundant amino acid in CFP, the two signals at 32.9 and 30.3 ppm proved that the small molecule amino acids hydrolyzed from chicken feathers in CFP-WP have successfully penetrated into the wood cell walls during the impregnation process, being beneficial for CFP-WP due to that boron can form salts with some of the -NH-CO- groups and fix onto wood matrix by heat-induced gelling of protein (Thevenon et al. 1997, 2003; Mazela and Polus-Ratajczak 2003; Ratajczak and Mazela 2007). This result was in line with the aforementioned CrI results in XRD analysis, which further confirms the prospective modification effects of CFP-WP.

Consequently, P_2 could be used as an ideal preservative formulation and could provide potential protection and durability for the treated wood during future application due to the penetration and reaction and/or interaction of the low molecule amino acids with wood components.

3.3 Crystalline structure analysis of CFP-WP treated wood

The X-ray diffraction patterns are depicted in Fig. 5 and the crystallinity indexes (CrIs) are summarized correspondingly in Table 3.

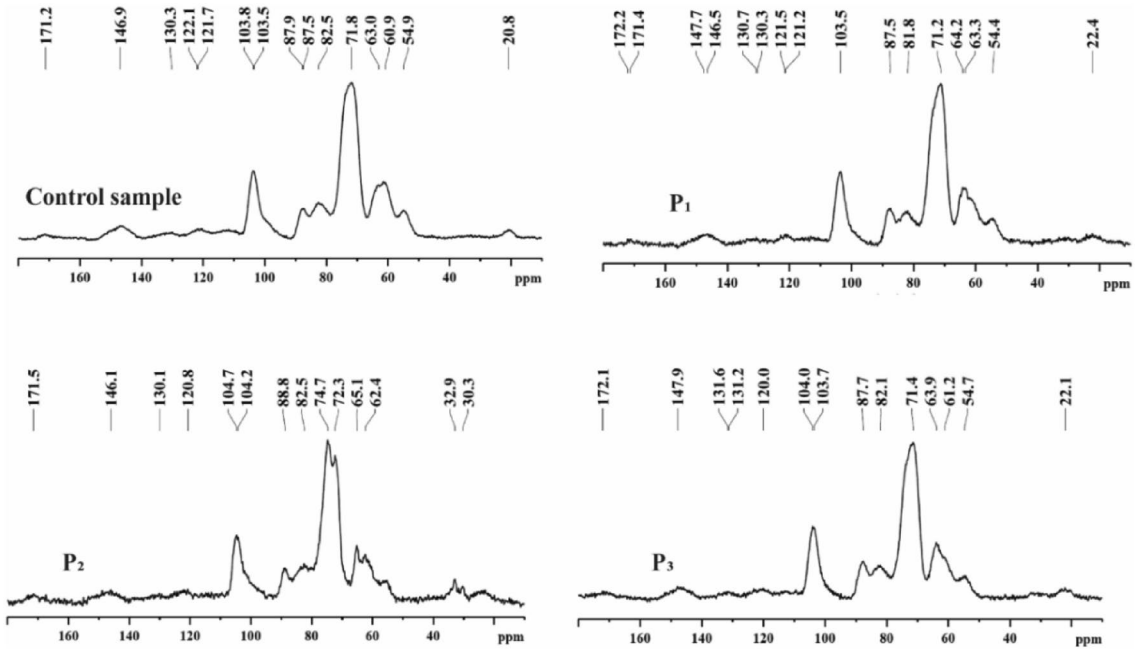

Fig. 4 CP/MAS ^{13}C-NMR spectra of wood samples

As can be seen from Fig. 5, all the XRD patterns showed typical cellulose I structure, with a broad peak from 14.8 to 16.5 and a sharp peak at 22.5º, indicating no transformation of the crystal structures in treated wood during the modification processes by CFP-WP. The CrIs of the wood samples treated by P_1, P_2, and P_3 dropped to 57.14, 49.70 and 52.62, respectively, compared to the CrI (60.10) of the control sample. This is because of the permeation of the amorphous protein of preservatives, which can contribute to the relatively reduced crystallinity. It is interesting to note that the CrI of the P_2 group was the lowest compared to that of the control and other treated wood, attributed to more penetration of amorphous protein into the wood cell walls, which was consistent with the results in the treatability analysis.

3.4 Thermal stability analysis (TGA) of CFP-WP treated wood

Thermogravimetric analysis is an important method to evaluate and understand the thermal stability of chemically modified materials, and both TGA and DTG curves of the preservative treated wood samples by different formulations are depicted in Fig. 6.

As portrayed from the DTG curves in Fig. 6, the content of solid residues in P_1 treated wood samples was close to that of control samples, due to the low contents of Cu and B in P_1. By contrast, the residual char values of samples treated by P_2 and P_3 significantly surpassed that of control samples and the P_1 group, due to the more active components Cu and B. It can also be seen from the TGA curves that the initial

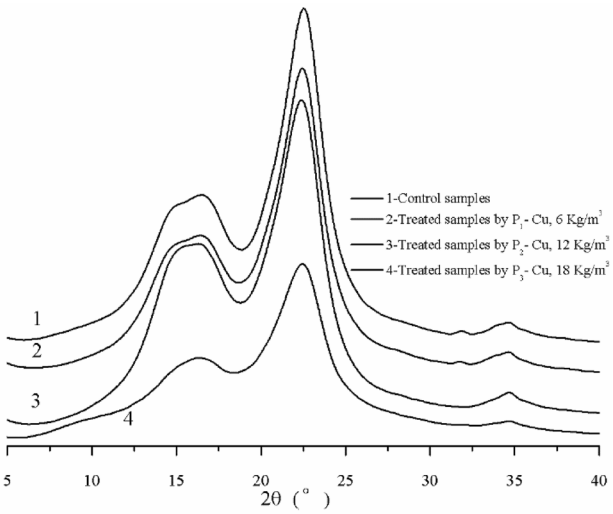

Fig. 5 XRD patterns of wood samples

Table 3 Crystallinities of wood samples

Formulations	C_rI
Control samples	60.10
Samples treated by P_1	57.14
Samples treated by P_2	49.70
Samples treated by P_3	52.62

pre-carbonization temperature of three treated wood samples were lower than that of control samples, as a consequence of the introduction of Cu and B elements, which could

promote char forming during the heating process (Helsen et al. 1999; Aydemir et al. 2016). Additionally, the eventual carbon residues of treated samples were all higher than that of control samples, indicating the role of CFP-WP played on the treated wood samples, and further confirming the penetration and fixation of CFP-WP onto wood structures.

3.5 Morphology observation

3.5.1 Distribution of Cu and B

To observe the microstructural changes and distribution of Cu and B in the wood cell walls, SEM–EDS analysis was carried out and the results are given in Table 4, Figs. 7, 8 and 9. There was no clear deposition of CFP-WP observed on wood cell walls of the treated wood samples (Fig. 7), indicating an effective distribution within the cell wall. Furthermore, SEM–EDS pictures in Fig. 8 evidenced that Cu and B penetrated into the treated wood cell walls uniformly, instead of deposition in the wood surface or lumen. It can also be seen in Table 4 that the contents of active elements Cu and B in samples treated by P_2 (Cu: 9.20%, B: 3.38%) and P_3 (Cu: 11.01%, B: 2.97%) exceeded that of samples treated by P_1 (Cu: 4.91%, B: 2.53%), which demonstrated the successful impregnation of sufficient amounts of active ingredients into the wood blocks and accordingly displayed anticipant modification effects. Meanwhile, the Cu content in the wood cell walls of P_3 was higher than that of P_2, whereas the contents of B and N both declined compared to P_2. This may be attributed to the more leachate of Cu in P_3 due to insufficient chelating with B and N compared to the P_2 group that possesses more content of protein. This hypothesis had been proved by the results in leachability in our previous study (Xia et al. 2020) and was consistent with the XRD and NMR analyses as well.

Table 4 Element distributions within cell walls of the treated wood samples

Elements	Control	P_1	P_2	P_3
B	1.68	2.53	3.38	2.97
C	44.69	40.52	39.03	40.28
N	0.000	3.10	4.08	3.82
O	51.27	47.88	43.19	40.89
Ca	0.98	1.06	1.12	1.03
Cu	1.38	4.91	9.20	11.01
Total	100	100	100	100

3.5.2 Morphology observation after decay test

To further observe the morphology of the treated wood after the decay test and investigate the protection efficacy of CFP-WP, the wood microstructures after 12 weeks of decay test were examined (Fig. 9). It can be seen that the integrated cell wall can barely be recognized in control samples, indicating that wood cell walls seriously degraded due to the fungal decay. In contrast, the cell walls were relatively intact in the three treated groups, confirming the effectiveness and protective function of CFP-WP, although some damaged cell walls still could be found in the P_1 group due to the insufficient amounts of efficient ingredients in preservative P_1. Compared with the appearance condition of the cell wall of the control and P_1 group wood samples, the integrality and preservation situation of the cell walls of the P_2 and P_3 groups were better than the control and P_1 group samples, which proved their superior protection efficiency.

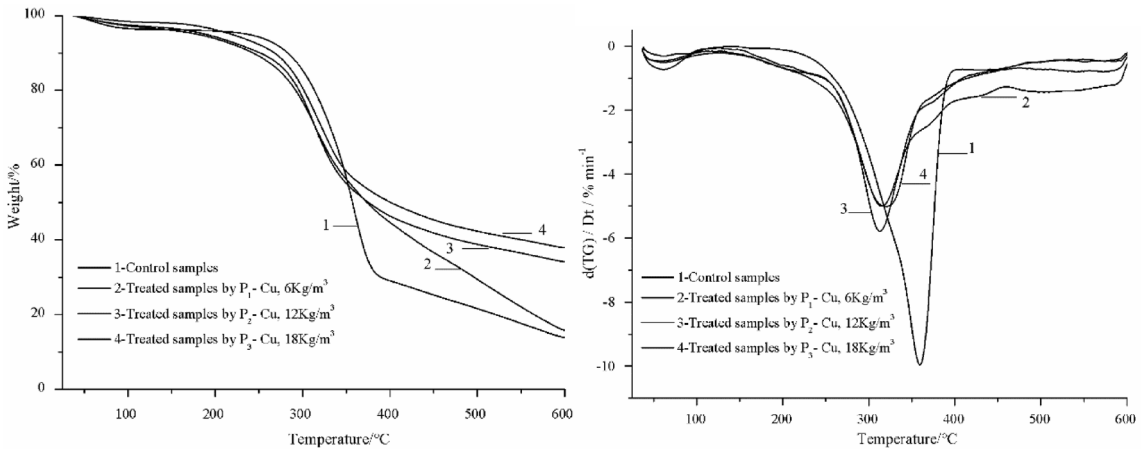

Fig. 6 TG/DTG spectra of wood samples

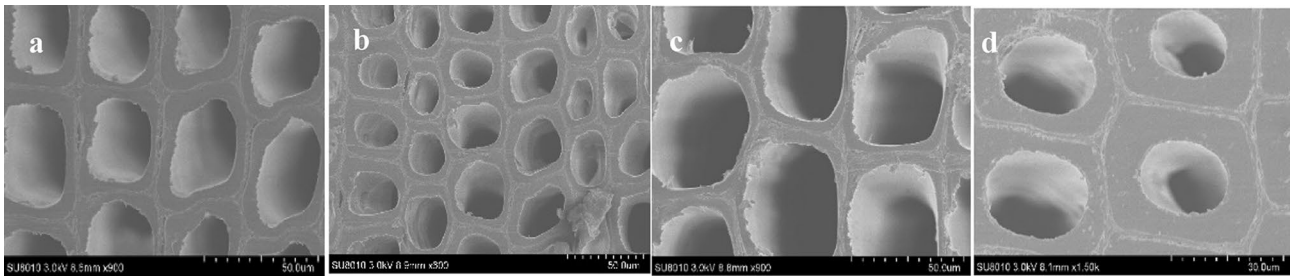

Fig. 7 SEM photographs of wood samples, **a** control, **b** treated with P_1, **c** treated with P_2, **d** treated with P_3

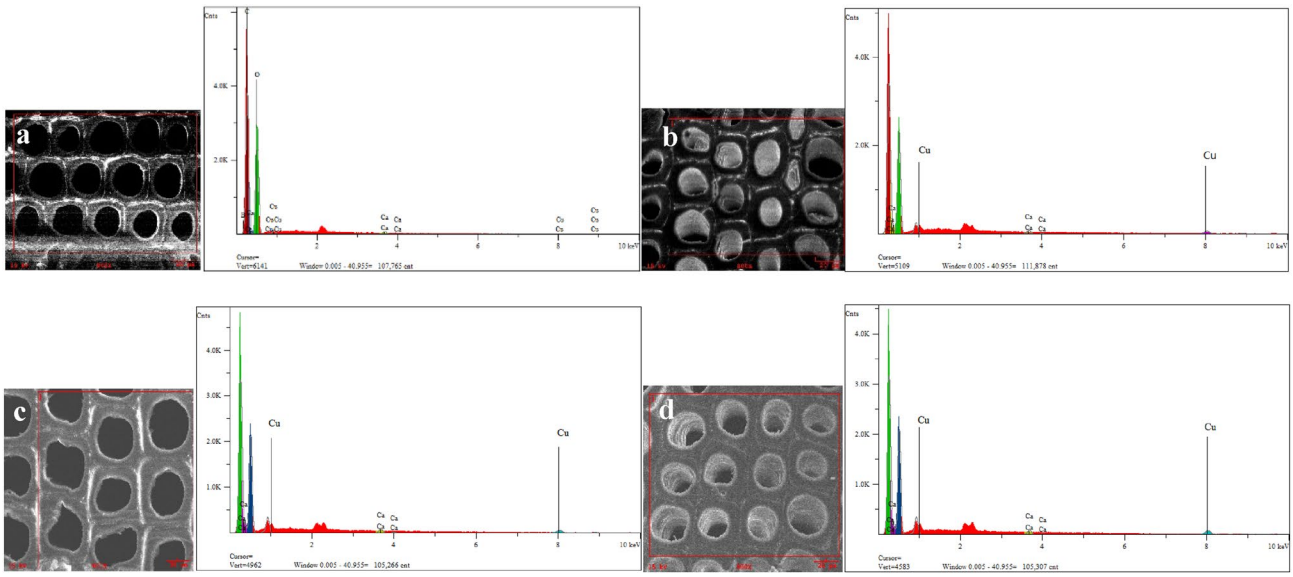

Fig. 8 SEM–EDS images showing the distributions of B, N, and Cu within the wood cell wall, **a** control, **b** treated with P_1, **c** treated with P_2, **d** treated with P_3

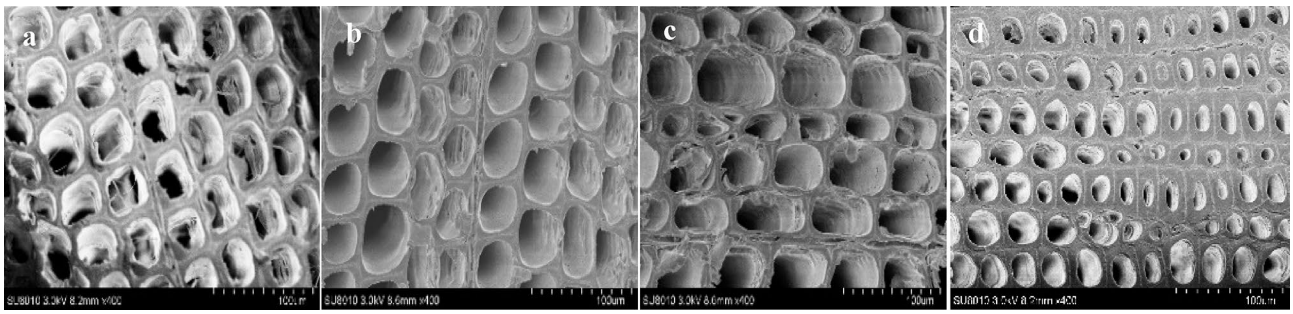

Fig. 9 SEM photographs of wood samples after 12 weeks decay test, **a** control, **b** treated with P_1, **c** treated with P_2, **d** treated with P_3

3.6 Production cost assessment and decay resistance of CFP-WP

To assess the production cost of CFP-WP, the evaluation of the CFP-WP cost collected from the prices of raw materials and additives is summarized in Table 5. The production cost of CFP-WP is nearly 30% lower than the normal commercial price of ACQ (approx. 210 €/tonne) as a result of the low price of the chicken feathers.

The results of wood samples against brown-rot fungi *G. trabeum* after decay resistance experiments are shown in Table 6 and Fig. 10. The mass losses were 20.45%, 10.88%,

Table 5 Unit prices of the materials used in CFP-WP production

Materials	Formulations	Copper sulfate	Sodium borate	CFP and additives	CFP-WP
Cost (€/tonne)	P_1	26	30	7–14	63–70
	P_2	52	61	14–21	127–134
	P_3	78	43	14–21	135–142

Table 6 Mass losses of wood samples

	Mass loss (%)	Standard deviation
Control	51.02	0.0285
P_1	20.45	0.0134
P_2	10.88	0.0120
P_3	12.13	0.0124

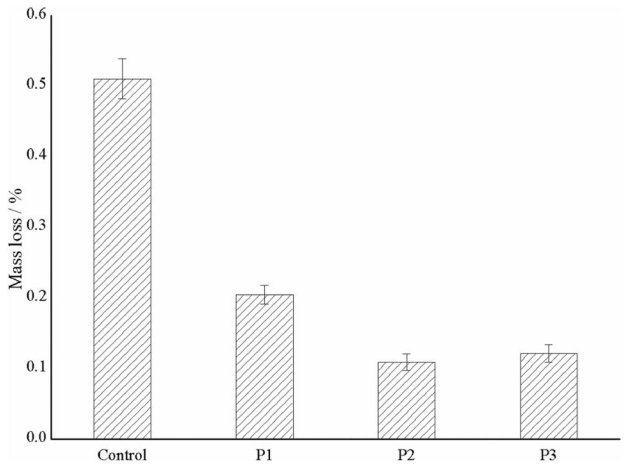

Fig. 10 Mass losses of control and treated samples after the decay test

and 12.13% for the wood samples treated by P_1, P_2, and P_3 respectively, compared to that of 51.02% of control samples, up to about 400% reduction in mass loss. There were reports about the mass loss in wood treated with commercial wood preservatives, such as ACQ with 12.99% of mass loss and CCA with 3.21% of mass loss (Kartal et al. 2015), but it's not easy to compare the mass loss of the treated wood due to the different tree species including diverse amounts of the active ingredient in various preservatives. Even though, the result of the decay test still demonstrated that the anti-decay effect of three CFP-WP formulations was excellent, which indicated the good and desired decay resistance of treated wood blocks. In addition, mass losses decreased considerably with the increase in the amounts of active ingredients. The mass loss of P_2 treated samples was slightly lower compared to that of P_3, due to the better fixation within wood of P_2. It can be concluded that the P_2 formulation can provide more efficient and long-term protection for wood products, which have less content of Cu and more content of B with low poisonousness, especially with higher content of the low molecule amino acids such as the valine penetrated into wood.

Furthermore, compared with soy protein-based or okara protein-based preservatives (Yang et al. 2006; Ahn et al. 2008), the results of decay experiments confirmed that CFP-WP is a more effective system to protect the wood with a simpler modification process in the ambient condition without vacuum and pressure, and at a lower price along with higher protein content (approx. 90% protein content, higher than approx. 37–42% in soy protein and 20% in okara) (Krishnan et al. 2007; Kim et al. 2011; Taskin 2013).

4 Conclusion

New CFP-WP preservative systems were successfully formulated by using chicken feathers as a natural source of protein and fixation agent to chelate Cu and B elements of wood preservatives. The efficacy of CFP-WP preservative against wood decay and effect on wood properties were investigated. The interactions of active ingredients of CFP-WP with wood constituents took place. Small molecule amino acids (hydrolyzed from chicken feathers) and CFP-WP were able to penetrate into wood blocks uniformly without deposition of cell lumen or cell wall surface. CFP-WP could protect wood against decay fungi efficiently, with about 400% reduction in mass loss after a decay test, and prospectively prolonged the wood service life accordingly. Particularly, the P2 preservative formulation proved a more efficient and appropriate environmentally benign system with higher preservative efficacy, with less content of Cu and more content of low toxicity B. The CFP-WP production was about 30% cheaper than that of conventional commercial wood preservatives in the market. CFP-WP could be a feasible alternative to the toxic CCA and other traditional wood preservatives to achieve low toxicity and cost, high protection efficacy, environmental benefit, and a simple and cleaner modification process.

Acknowledgements The authors are grateful for the financial support by the Regional Project of National Natural Science Foundation of China (32260362, 31860186, 31360157), the Joint project of Yunnan Agricultural Basic Research (202101BD070001-058), the 111 Project (D21027) and the Yunnan Province Natural Science Key Foundation (202201AS070152).

Author contributions YX: Formal analysis, Investigation, Data curation, Writing-original draft, and Funding acquisition. AM, YZ: Data analysis, Paper content and grammar revision. CZ: NMR technique analysis. SD, BL: Visualization, Formal analysis. JW: Validation, Supervision. MF: Supervision, Writing—review and editing.

Data availability The data that support the findings of this study are available on request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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