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THE EFFECT OF COMPOSITE MODIFIED BORON-BASED WATERBORNE FLAME-RETARDANT COATING ON COMBUSTION PERFORMANCE OF BAMBOO DECORATIVE FILAMENT

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ABSTRACT

To address the flammability of bamboo decorative filament, seven waterborne composite flame-retardant coating systems were developed using waterborne acrylic resin as the film-forming matrix, with boric acid, borax, ammonium polyphosphate (APP), nano-SiO_2, and disodium octaborate tetrahydrate (DOT). The filament was treated as primer-only, topcoat-only, and combined primer/topcoat application. The combustion performance was evaluated by a cone calorimeter following ISO 5660-1: 2002. The results indicated that in the primer-only coating system, the boric acid/borax/disodium octaborate tetrahydrate composite system reduced total smoke production (TSP) by 11.90%, while the total heat release (THR) of the boric acid/borax/disodium octaborate tetrahydrate/ammonium polyphosphate composite system decreased by 18.83%. In the topcoat-only system, the boric acid/borax single-component system exhibited the optimal comprehensive performance, which the peak value of heat release rate (HRR) and the TSP decreased 13.54% and 8.24%, resp. In the combined primer-topcoat systems, THR reductions of 10.99% and 10.21% were achieved. Notably, nano-SiO_2/boric acid/borax exhibited superior smoke suppression performance, with a 14.12% decrease in TSP, attributed to the synergistic physical barrier effect between the silicate network formed by nano-SiO_2 and the boron-based glassy protective layer.

KEYWORDS: Bamboo decorative filament, water-based paint, flame retardant, heat release, smoke release.

INTRODUCTION

Bamboo is a renewable, eco-friendly material with a short growth cycle and excellent mechanical properties, and it has been widely used in architectural decoration, furniture manufacturing and other relevant fields (Qi et al. 2025; Wu et al. 2025). Bamboo decorative filament has emerged as a new preferred choice for interior decoration due to their unique flexibility and decorative aesthetics (Li et al. 2024; Lyu et al. 2025). However, the high content of cellulose and hemicellulose renders it inherently flammable, which severely restricts its application in high-end scenarios (Chai et al. 2025; Wang et al. 2019).

At present, flame-retardant treatment of bamboo is confronted with prominent technical bottlenecks. Conventional deep impregnation methods like high-temperature soaking and vacuum pressurization cause mechanical property deterioration (He et al. 2024; Hu et al 2025). Bamboo's anisotropic structure results in heterogeneous vascular bundle and parenchyma cell distribution, leading to disparate hygroscopic expansion coefficients across directions. Flame-retardant infiltration induces uneven internal stress, poor dimensional stability, and warpage deformation (Zhang et al. 2018; Jin et al. 2015). In addition, the surface visual performance of bamboo is compromised following such treatments. Studies have demonstrated that phenolic compounds in bamboo undergo oxidation and polymerization under high-temperature conditions, leading to surface darkening (Wen et al. 2026). Moreover, vacuum pressurization treatment accelerates the migration of flame retardants toward the bamboo surface, which induces undesirable surface discoloration (Li et al. 2018). The enhancement of flame-retardant performance is accompanied by unresolved issues including the poor aging and leaching resistance of flame retardants, thus limiting the comprehensive application value of such flame-retardant treatment methods.

Flame-retardant coating treatment has emerged as a pivotal research direction for bamboo flame-retardant modification, owing to its simple operation and cost controllability (Yang et al 2024; Wang et al 2024). Compared with solvent-based coatings, water-based coatings exhibit lower VOC emissions, which aligns with the low-carbon development trend. Acrylic resin coatings boast excellent film-forming properties, weather resistance, contamination resistance, and acid-alkali resistance, while preserving the original appearance of coated substrates; thus, they have been widely applied in the decorative coating of bamboo and wood materials (Ling et al 2020; Xu et al 2023). Boron-based flame retardants, as low-toxic, highly efficient, smoke-suppressant and eco-friendly flame-retardant additives, can form an effective thermal insulation barrier via their glassy coating within 30 s at a high temperature of 450°C. They exert flame-retardant effects in both the condensed and gas phases: the condensed phase inhibits the transfer of heat and oxygen, while the gas phase scavenges combustion-generated free radicals (Liu et al 2023; Li at al 2021; Li et al 2019). However, single-component boron-based flame retardants suffer from inherent drawbacks including limited flame-retardant efficiency and poor leaching resistance. Studies have confirmed that the flame-retardant efficiency of single boron-based flame retardants is inferior to that of phosphorus-nitrogen synergistic systems (Zhao et al 2024; Yu et al 2024). Thus, constructing a synergistic flame-retardant system via multi-component compounding has emerged as an effective strategy to enhance their comprehensive performance.

Based on the above, this study builds upon the existing research foundation of boron-based flame-retardant materials, takes acrylic resin as the film-forming matrix, and constructs a boron-based multi-component composite flame-retardant water-based coating system (Zhang et al 2022). It systematically investigates the effects of different composite formulations on the combustion performance of bamboo filament decorative materials, and screens out the optimal coating formulation and finishing process. This study not only effectively addresses the problem of material performance degradation caused by traditional bamboo flame-retardant treatment, but also enhances the flame-retardant and smoke-suppressant properties of bamboo filament decorative materials while improving their physicochemical properties and surface decorative effects.

MATERIAL AND METHODS

Material

Decorative bamboo filament (*Phyllostachys edulis* (Carr.) J.Houz.) was purchased from Tongshan Shengtai Bamboo and Wood Products Co., LTD. Materials were cut into sheet-like specimens with dimensions of 100 mm (length)×100 mm (width)×1.2 mm (thickness) (Fig. 1h), and each individual bamboo filament measured 100 mm (length)× 2 mm (length)×1.2 mm (length) mm (Fig. 1g). The processing procedure of bamboo decorative filament was shown in Fig. 1. After being air-dried, the moisture content was 7%.

The primary difference between the primer and topcoat based on waterborne acrylic resin coatings resides in their solid content. The primer has a solid content of 30±1% and exhibits stronger adhesion to the substrate, whereas the topcoat has a solid content of 20±1% and possesses superior film-forming performance, which were purchased from Shanghai Banbaihe Coatings Co., Ltd. Ammonium polyphosphate and boric acid were purchased from Shanghai Mindray Chemical Technology Co., Ltd. Borax was purchased from Tianjin Damao Chemical Reagent. Disodium octaborate tetrahydrate from Tianjin Xienen Biochemical Technology Co., Ltd, trisodium phosphate from Tianjin Damao Chemical Reagent Factory and nano silica from Shanghai Maikun Chemical Co., Ltd. All chemicals were purchased in analytical grade.

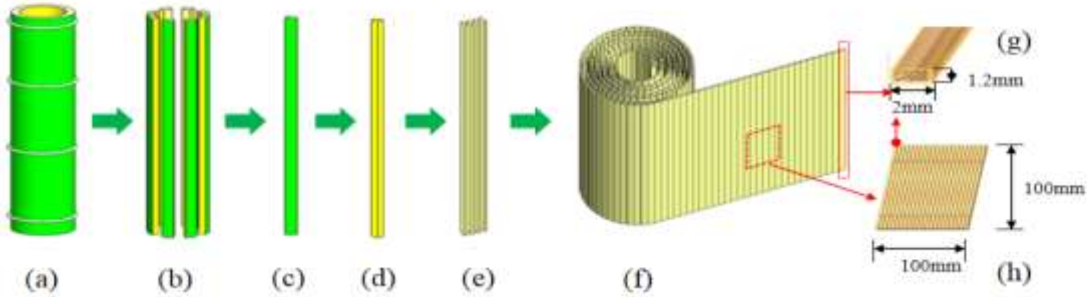


Fig. 1: Processing of bamboo decorative filament: (a) Bamboo tube; (b) slicing; (c) bamboo strips; (d) slicing bamboo strips; (e) bamboo silk; (f) bamboo decorative filament; (g) dimensioning of bamboo silk; (h) dimensioning of bamboo decorative filament.

Preparation of composite flame retardants

Five inorganic salt flame retardants, namely boric acid (B), borax (BX), ammonium polyphosphate (APP), nano-silica ($nSiO_2$), and disodium octaborate tetrahydrate (DOT), were compounded for subsequent experiments. Boric acid (20 g) was weighed using an electronic balance and dissolved in 60 g of deionized water. The stirring apparatus was then activated and the temperature was set to 55°C. Following 30 min of stirring, 20 g of borax was weighed and added to the above mixture for complete dissolution, yielding the boric acid/borax flame retardant system. The flame retardant systems containing ammonium polyphosphate or disodium octaborate tetrahydrate were prepared via the identical method.

For the preparation of the $nSiO_2$ flame retardant system, trisodium phosphate (TP) was selected as the dispersant. Briefly, 10 g of trisodium phosphate was weighed and dissolved in 89 g of deionized water under stirring at 40°C until complete dissolution. Subsequently, 1 g of $nSiO_2$ was added to the solution, followed by stirring at room temperature for 3.5 h, ultrasonic treatment for 2 h, and final low-speed stirring at room temperature for 0.5 h. On the basis of the above four flame retardant systems, composite flame retardant formulations were prepared, with the component ratios of each group detailed in Tab. 1.

Tab. 1: Preparation conditions for fire retardant coating.

Nº	Flame retardant composition	Ratio of components in water solution (%)
C	Without flame retardant	0
1	Boric acid/borax	20/20
2	Trisodium phosphate/$nSiO_2$/boric acid/borax	10/1/20/20
3	Boric acid/borax/ammonium polyphosphate	20/20/2
4	Trisodium phosphate/$nSiO_2$/boric acid/borax/ammonium polyphosphate	10/1/20/20/2
5	Trisodium phosphate/$nSiO_2$/boric acid/borax/disodium octaborate tetrahydrate	10/1/20/20/10
6	Boric acid/borax/disodium octaborate octahydrate/ammonium polyphosphate	20/20/10/2
7	Boric acid/borax/disodium octaborate octahydrate/ammonium polyphosphate/trisodium phosphate/$nSiO_2$	20/20/10/2/10/1

Sample preparation

Three flame-retardant modifier systems were prepared via physical blending of flame retardants with waterborne acrylic resin coatings (Huang et al 2018). Specifically, these three systems were fabricated based on the primer, topcoat, and their mixed coating (1:1), respectively, with the corresponding flame-retardant components incorporated into each coating type. The flame retardant and waterborne coating were mixed at a mass ratio of 2:3. For each formulation, 32 g of the flame retardant (Tab. 1) was weighed and added to 48 g of the waterborne coating, followed by stirring on a magnetic stirrer until a homogeneous mixture was obtained, yielding 80 g of flame-retardant waterborne coating per batch. Subsequently, dip a brush in the mixed coating and apply it evenly on the surface of the bamboo silk. When the surface of the sample coating was dry, recoating could be performed until the prepared coating was completely used up. After the final coating, the samples were placed at room temperature until the coating was fully cured, with the total coating loading strictly controlled at 80 g/m^2. Finally, the bamboo decorative materials were cut into specimens with dimensions of 100 × 100 × 1.2 mm for combustion performance testing. The detailed preparation and coating process is illustrated in Fig. 2.

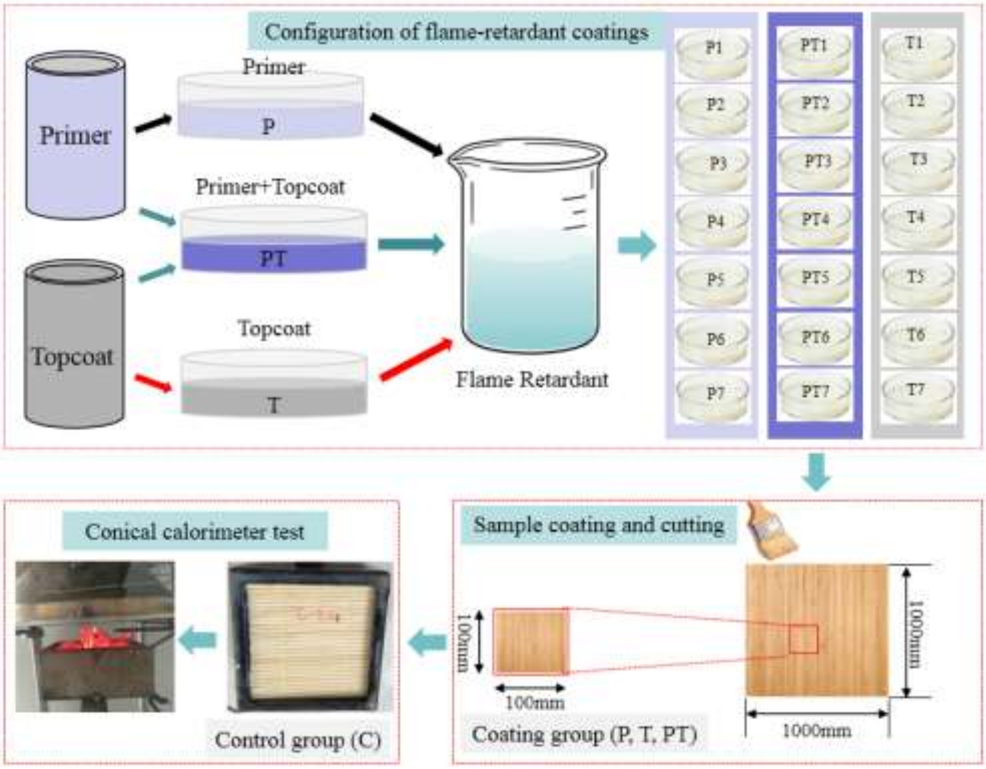


Fig. 2: Sample preparation process.

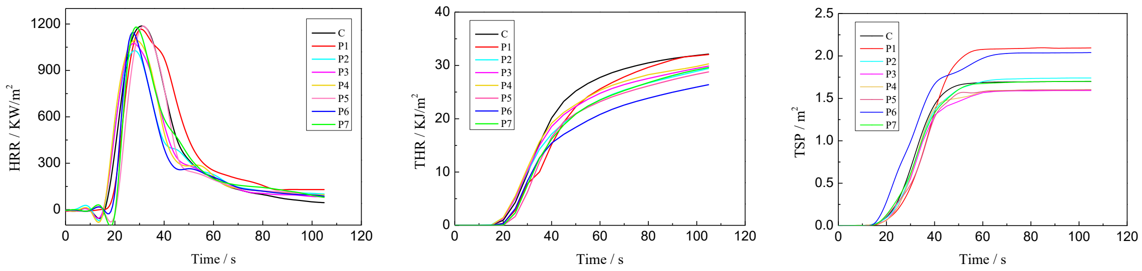
Combustion performance by cone calorimeter

The combustion performance of specimens with different flame-retardant coatings was tested by a cone calorimeter (FTT0242, Fire Testing Technology Co. Ltd., West Sussex, UK) according to ISO 5660 -1: 2002 (E) Reaction to fire tests. Heat release, smoke production and mass loss rate. Part 1: Heat release rate (cone calorimeter method), which was used to investigate the effects of flame-retardant treatment on the indexes of bamboo filaments such as heat release rate (HRR), total heat release (THR) and total smoke production (TSP). All surfaces of the specimen except the heating surface were wrapped with aluminium foil to minimize interference from external factors. To prevent heat transfer, thermal insulation cotton was used for heat insulation, and the specimen was irradiated under a heat flux of 50 KW/m^2. The specimens were placed horizontally with their heating surfaces facing upward, and thermal radiation was applied in the vertical direction. Ignition was achieved via an electric arc, data were recorded every 5 s, and the test was completed after 105 s of combustion starting from ignition. All combustion parameters were automatically recorded.

RESULTS AND DISCUSSION

Combustion performance of flame-retardant primer coating treatment

The heat release performance of materials is a core index for characterizing their combustion behaviour, fire hazard and flame-retardant modification efficiency, which is mainly quantified by heat release rate (HRR) and total heat release (THR) (Huang et al 2021). The peak value of HRR reflects the intensity and spread potential of fire, where a higher peak value and an earlier occurrence time correspond to more prominent fire hazards. In contrast, THR represents the total energy reserve of materials during combustion, with a larger value indicating a stronger persistence of fire and greater hazards from thermal radiation. The synergistic effect of these two indices determines the flame-retardant performance of materials (Xu 2023).



(a) *(b)* *(c)*

Fig. 3: HRR (a), THR (b) and TSP (c) curves of the primer-coated group.

The heat release rate (HRR), total heat release (THR) and total smoke release (TSP) curves of specimens before and after flame-retardant primer coating are presented in Fig. 3. As can be seen within 0–105 s, all groups exhibited only one distinct exothermic peak in their HRR curves (Fig. 3a). A comparison of the peak values indicated that the HRR peak values of all specimens decreased to varying degrees after flame-retardant coating treatment.

The time to ignition (TTI) of specimens coated with primers formulated by multi-component compounding of boric acid/borax was nearly consistent across all groups (Tab. 2). The HRR peak values of P1-P7 decreased by 1.67%, 15.78%, 11.91%, 8.42% and 2.03%, 12.20% and 2.17%, respectively. Compared with Group C, the reduction amplitudes were relatively small. In terms of the mean value of HRR, all coated groups except P1 exhibited decreasing trends, with reduction ranges of 0.44%-17.04%. Among them, P6 achieved the highest reduction at 17.04%. Collectively, these HRR parameters indicate that the formula for P6 effectively inhibits combustion rate, thereby reducing sustained heat release capacity and overall combustion hazard levels.

It can be observed that during the combustion process, different coating components and flame retardant addition processes all led to a decrease in the THR value of bamboo filaments (Fig. 3b). Specifically, in the early stage of combustion (0-35 s), the THR of bamboo filaments coated with the modified topcoat increased relatively slowly, indicating that the heat suppression effect of the coating was effectively improved. Following topcoat degradation after 35 s, the THR curve slope increased sharply: P2, P3, and P4 exhibited growth rates similar to Group C, while P1, P5, P6, and P7 showed slower increases. After 35 s, the slope of the THR curve gradually decreased. Throughout combustion, P5 and P6 exhibited favourable heat suppression effects, which decreased 10.40% and 18.83%, respectively. The best heat suppression effect of Group P6 was mainly attributed to boric acid and borax, the primary flame-retardant components among the boron compounds in the phosphorus-nitrogen-boron composite flame retardant. When heated, a glassy inorganic intumescent coating was formed by these compounds; they were dehydrated at high temperatures, carbonization was promoted, and further thermal decomposition of the material as well as the overflow of combustible substances were hindered (Li et al 2019; Cui et al 2016). In addition, the synergistic flame-retardant effect between boric acid, borax and ammonium polyphosphate has been demonstrated by previous studies (Fan et al 2022; Jiang et al 2020).

Tab. 2: Heat release-related parameters of bamboo filament specimens coated with primer.

Serial number	Time of HRR peak (s)	HRR peak value (kW/m^2)	Mean HRR (kW/m^2)	Ignite time (s)	THR T105 (MJ/m^2)
C	30	1183.24	290.77	17	32.13
P1	30	1163.48	377.13	16	32.06
P2	28	996.58	268.03	16	29.34
P3	28	1042.28	275.29	18	29.88
P4	28	1083.65	289.62	17	30.31
P5	31	1159.24	261.72	20	28.79
P6	27	1038.84	241.22	18	26.08
P7	28	1157.61	269.43	20	29.59

Smoke release behaviour during material combustion is a critical criterion for evaluating the flame-retardant modification efficiency. In fire scenarios, smoke from burning materials severely reduces visibility in fire zones, hindering evacuation and rescue operations, while toxic components become the primary cause of casualties. The total smoke release (TSP) reflects the cumulative smoke production level of materials from ignition to the end of combustion; the specific extinction area (SEA) directly characterizes the light obscuration capacity of combustion-generated smoke, and the mean CO/CO_2 production indicates the degree of complete oxidative combustion, which further reflects the generation law of toxic flue gas and the intensity of combustion reactions. All these indicators serve as important bases for assessing the smoke suppression performance of flame-retardant systems.

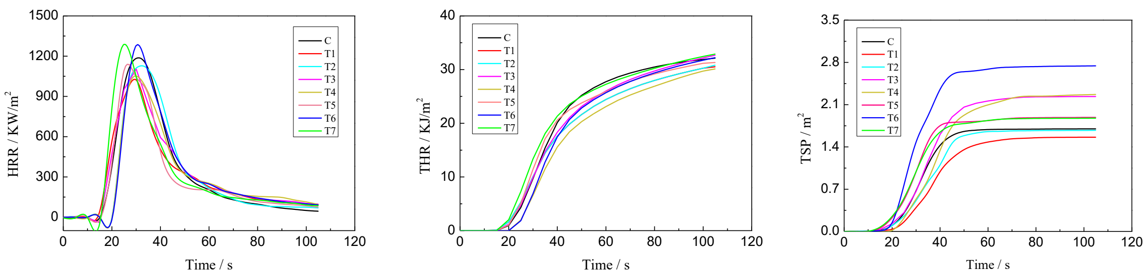
The TSP curves and related parameters of bamboo filament decorative materials treated with various flame-retardant coatings were presented in Fig. 3c and Tab. 3. As shown in Fig. 3c, compared with the control group PC, the average yields of carbon monoxide (CO) and carbon dioxide (CO_2) both exhibited a decreasing trend after flame-retardant coating treatment. The mean value of SEA values showed diverse variation tendencies, with P5 presenting the maximum reduction in SEA by 8.80%. The TSP of P1, P2 and P6 increased, while that of P3, P4, P5 and P7 decreased by 6.47%, 7.06%, 12.94% and 7.64%, respectively. Among these groups, P5 exhibited the optimal inhibitory effect on TSP. The phenomenon indicates that the boron-based compounds, nano-silicon dioxide (nano-SiO_2) and disodium octaborate tetrahydrate exert a synergistic effect, which jointly promotes the formation of a carbon layer at high temperatures and thus reduces smoke generation during combustion. This finding was consistent with relevant conclusions reported in previous studies, which indicated that nano-silica exerted an obvious synergistic effect with other components at low loading levels, thereby improving the flame retardant properties of the material (Li et al 2025). The results before and after flame-retardant primer treatment revealed that P5 was superior to other groups in both heat and smoke suppression, which was decreased 10.40% (THR) and 11.90% (TSP), respectively.

Tab. 3: Smoke release-related parameters of bamboo filament specimens coated with primer.

Serial number	Mean SEA (m^2/ kg)	Mean CO_Y (kg / kg)	Mean CO_{2Y} (kg / kg)	TSP T105 (m^2)
C	441.48	0.21	6.98	1.70
P1	525.73	0.10	6.92	2.09
P2	481.29	0.09	6.35	1.72
P3	447.89	0.10	6.57	1.59
P4	439.14	0.10	6.51	1.58
P5	402.64	0.09	6.41	1.48
P6	525.26	0.07	6.33	1.76
P7	423.35	0.12	6.24	1.57

Combustion performance of flame-retardant topcoat coating treatment

The HRR, THR and TSP curves of bamboo filaments coated with compound flame-retardant coatings as topcoats were presented in Fig. 4, and the combustion data of the topcoat groups was shown in Tab. 4.



(a) *(b)* *(c)*

Fig. 4: HRR (a), THR (b) and TSP (c) curves of the topcoat group.

Fig. 4a shows that all specimens exhibited a single heat release peak within 0-105 s. Except that the peak occurrence time of HRR for P7 was advanced by 5 s, the peak occurrence times of the remaining coated groups were consistent with that of the group C. Compared with the group C, the peak heat release rate (pk_{HRR}) values of bamboo filaments treated with different single-component (T1) flame-retardant coatings all decreased to varying degrees, but the reduction amplitudes were slight. The bamboo filaments coated with the boric acid: borax modified topcoat showed the lowest pk_{HRR}, which was only 13.54% lower than that of the untreated samples. For bamboo filaments treated with different dual-component (T2 and T3) flame-retardant coatings, the pk_{HRR} values of the flame-retardant treated samples showed little variation, decreasing by 6.13% and 6.67% compared with the untreated samples, resp. Among the multi-component groups (T4-T7), T4 and T5 exhibited the most significant decreases in pk_{HRR}, with reductions of 11.11% and 11.83%, respectively. The possible reason is that Nano-SiO_2 has excellent thermal stability (Wang et al 2026). When compounded with boron-, phosphorus- and nitrogen-based flame retardants, a dense and stable protective barrier is formed during thermal decomposition, which blocks oxygen and heat transfer into the material matrix and consequently reduces heat release (Xu 2022; Dan et al 2025).

Tab. 4: Heat release-related parameters of topcoat group.

Serial number	Time of HRR peak (s)	HRR peak value (kW/m^2)	Mean HRR (kW/m^2)	Ignite time (s)	THR T105 (MJ/m^2)
C	30	1183.24	290.77	17	32.13
T1	30	1023.00	290.22	17	30.15
T2	30	1110.68	279.55	22	30.79
T3	30	1104.37	288.00	19	33.14
T4	30	1051.81	281.84	21	29.71
T5	30	1043.27	298.03	20	31.33
T6	30	1279.14	294.08	25	30.38
T7	25	1288.01	298.47	19	32.90

As shown in Fig. 4b, in terms of THR values, the entire heat release process was characterized by an initial rapid increase, followed by gradual stabilization until the end of the combustion reaction. In the early stage of combustion (0-35 s), the THR of bamboo filaments coated with T4 and T6 modified topcoats increased at the slowest rate, which indicated that the heat inhibition performance of the coatings was effectively improved. After 35 s, with the damage of the topcoat layer, THR rose sharply before stabilizing. While THR increased for T3 and T7, other groups exhibited reductions, with T4 achieving the maximum decrease (7.53%). Collectively, HRR and THR analyses demonstrate T4's superior heat inhibition performance, where the Nano-SiO_2/boric acid:borax/ammonium polyphosphate topcoat formulation outperformed other groups.

The TSP curves and related parameters of bamboo filaments treated with flame-retardant topcoats are presented in Fig. 4c and Tab. 5, respectively. Figurative data indicate that only T1 and T2 demonstrated smoke suppression effects, reducing TSP by 8.24% and 1.18% respectively. The flame-retardant components of the topcoats for these two groups were boric acid/borax and nano-SiO_2/boric acid/borax, respectively, and their smoke suppression effects were essentially attributed to the smoke suppression activity of boron-based compounds. When boric acid and borax were compounded, boric acid mainly played a role in catalysing char formation and free radical scavenging, while borax excelled in forming a glassy barrier layer and achieving endothermic cooling. The synergistic effect of the two components could optimize the char layer structure, extend the duration of barrier protection, and thus significantly reduce the total smoke production (Zhang et al 2022).

Nano-SiO_2 incorporation slightly increased TSP, owing to nanoparticle agglomeration in the flame-retardant system. Poor dispersion of Nano-SiO_2 would reduce the efficiency of boron-based components in catalysing the char formation of cellulose, leading to an increase in small-molecule flammable volatiles generated during pyrolysis. This further caused a rise in the porosity of the char layer, thereby destroying its continuity and ultimately resulting in a higher TSP. This phenomenon is consistent with the conclusion that nano-particles exert negative interference on the physical barrier effect of flame-retardant systems (Wang et al 2023; Zhang et al 2022). Critically, all multi-component topcoats exhibited higher TSP than untreated samples, indicating that simply physical blending of multi-component flame retardants-without addressing dispersion stability and component compatibility-fails to achieve optimal flame-retardant and smoke suppression performance.

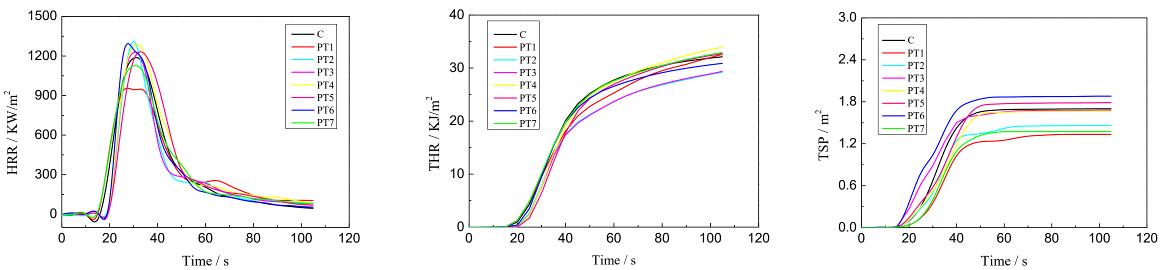
Tab. 5: Smoke release-related parameters of bamboo filament specimens coated with topcoat.

Serial number	Mean SEA (m^2/ kg)	Mean CO_Y (kg / kg)	Mean CO_{2Y} (kg / kg)	TSP T105 (m^2)
C	441.48	0.21	6.98	1.70
T1	513.40	0.11	6.23	1.56
T2	568.40	0.11	6.09	1.68
T3	557.51	0.12	6.67	2.23
T4	516.63	0.11	6.22	2.67
T5	445.36	0.10	6.53	1.89
T6	469.76	0.16	6.58	2.74
T7	458.73	0.15	6.61	1.88

Tab. 5 indicates reduced average CO and CO_2 yields in flame-retardant-coated bamboo filaments versus Group C. This was because the flame retardants blocked the penetration of oxygen into the substrate during combustion, reduced the oxygen concentration in the combustion zone, and thus prevented the full oxidation of flammable volatiles generated by substrate pyrolysis. Consequently, incomplete combustion simultaneously decreased CO_2 conversion and CO production. When ammonium polyphosphate (APP) was incorporated, its high-temperature decomposition generated polyphosphoric/metaphosphoric acids. While these acids catalysed char formation and produced intumescent layers suppressing gas-phase reactions, partially decomposed phosphorus residues and detached carbon particulates escaped with flue gases. This increased solid particulates in smoke, elevating specific extinction area (SEA) (Zhang et al 2024). Collective analysis of pre/post-treatment heat and smoke release data reveals T1's superior performance in both heat and smoke suppression, though with modest index reductions of only 6.16% and 8.24%, respectively.

Combustion performance of flame-retardant primer and topcoat coating treatment

The HRR, THR and TSP curves of bamboo filaments coated with compound flame-retardant primer and topcoat coating were presented in Fig. 5, and the combustion data was shown in Tab. 6.



(a) *(b)* *(c)*

Fig. 5: HRR (a), THR (b) and TSP (c) curves of the primer and topcoat group.

As can be seen from Fig. 5a, the HRR curve of the samples first plateaus, then rises sharply at a specific time point, indicating ignition of the samples. After reaching the peak, the curve gradually declines until combustion is complete. Based on the summarized HRR data, only a single heat release peak was observed throughout the combustion process, with the maximum heat release peak occurring within the range of 0-40 s; the time to peak basically fell within 30-35 s. The ignition time of the flame-retardant treated groups was delayed by 1-6 s relative to the group C (Tab. 6). In terms of peak changes, only the peak heat release rates (pk_{HRR}) of PT1 and PT7 exhibited a decreasing trend, with reductions of 20.21% and 4.83%, resp. For the mean value of HRR, the performance varied across all groups: the single-component group (PT1) and two-component groups (PT2 and PT3) all showed a decreasing trend, whereas only PT6 in the multi-component groups exhibited a decline. PT2 exhibited the maximum reduction in the mean value of HRR, with a decrease of 11.01%.

Tab. 6: Heat release-related parameters of primer and topcoat group.

Serial number	Time of HRR peak (s)	HRR peak value (kW/m^2)	Mean HRR (kW/m^2)	Ignite time (s)	THR T105 (MJ/m^2)
C	30	1183.24	290.77	17	32.13
PT1	30	944.08	277.83	17	30.67
PT2	30	1310.03	258.76	23	28.60
PT3	30	1227.40	260.58	22	28.85
PT4	30	1274.71	307.62	23	33.95
PT5	35	1205.08	295.86	23	32.72
PT6	30	1248.13	275.95	21	30.52
PT7	30	1126.07	297.67	19	32.94

The two-component groups (PT2, PT3) achieved markedly lower THR than other specimens, decreasing by 10.99% and 10.21% compared with group C (Fig. 5b). This demonstrate that the synergistic effects of flame-retardant components can be effectively exerted during combustion when two-component flame-retardant systems with favorable heat suppression performance are co-incorporated into both the primer and topcoat for the surface finishing of bamboo silk decorative materials. For PT2, the nano-silica and boric acid/borax within the primer-topcoat composite system exert not only a physical barrier effect but also a chemical synergistic interaction: nano-silica forms a dense silicate network structure during combustion, which effectively blocks the transfer of heat and oxygen (Chen 2017). Meanwhile, the boron-based compounds melt at high temperatures to form a glassy protective layer, thereby further enhancing the structural stability of the char layer (Wang et al 2014). In PT3, ammonium polyphosphate (APP) decomposes to polyphosphoric acid, catalysing substrate dehydration/carbonization. Meanwhile, boron compounds act as charring catalysts, boosting intumescent efficiency under the synergistic action of nitrogen and boron elements, ammonia gas released from APP decomposition reacts with boron-based compounds to form boron nitride, which further improved the gas-phase flame-retardant effect (Zhao 2019). The TSP curves of bamboo filaments coated with compound flame-retardant primer and topcoat coating were presented in Fig. 5c, and the Smoke release-related parameters in Tab. 7.

As can be seen from Fig. 5 and Tab. 7, the multi-component groups exhibited poor smoke suppression performance following flame-retardant coating treatment. In contrast, the TSP of the single-component group (PT1) and two-component groups (PT2 and PT3) all showed a decreasing trend, with reductions of 21.76%, 14.12% and 1.18%, respectively. PT1 and PT2 yielded the most effective smoke suppression effects; the flame-retardant coating formulations for these two groups were boric acid/borax and nano-SiO_2 /boric acid /borax, respectively, which was largely consistent with the smoke suppression performance observed for the topcoat-only groups.

Tab. 7: Smoke release-related parameters of topcoat-coated group.

Serial number	Mean SEA (m^2/kg)	Mean CO_Y (kg/kg)	Mean CO_{2Y} (kg/kg)	TSP T105 (m^2)
C	441.48	0.21	6.98	1.70
PT1	362.46	0.07	6.44	1.33
PT2	382.51	0.10	6.31	1.46
PT3	332.42	0.10	6.22	1.68
PT4	371.98	0.12	6.58	1.67
PT5	383.41	0.11	6.40	1.79
PT6	327.44	0.13	5.94	1.88
PT7	355.63	0.11	6.76	1.37

Additionally, the mean values of SEA, CO, and CO_2 yields all exhibited a decreasing trend, demonstrating that the combined primer-topcoat flame-retardant treatment achieved a superior smoke suppression effect compared to single-layer coating treatment. Compared with control group C, the yields of SEA, CO, and CO_2 in the flame-retardant treatment groups all decreased to varying degrees. Specifically, the maximum reduction in CO emission was achieved in the PT1 group, with a decrease of 66.67%, while the PT6 group exhibited the most pronounced reductions in SEA and CO_2 yields, by 25.76% and 14.90%, respectively.

CONCLUSIONS

(1) Boric acid/borax/disodium octaborate tetrahydrate (P5) and boric acid/borax/ disodium octaborate tetrahydrate/ammonium polyphosphate (P6) exhibited outstanding performance in the multi-component composite systems of the primer groups. P5 presented the optimal smoke suppression effect with a 11.90% reduction in TSP, while P6 showed the best heat suppression effect with an 18.83% reduction in THR，which should be noted that the physical mixing of flame retardants with topcoats fails to achieve simultaneous heat and smoke suppression effects. *(2)* The single-component boric acid/borax system (T1) exhibited the optimal comprehensive performance among the topcoat groups. Its peak heat release rate (pk_{HRR}) was reduced by 13.54% relative to the control group, with a concomitant 8.24% decrease in total smoke release. In contrast, the two-component and multi-component systems suffered from impaired char layer integrity caused by nanoparticle agglomeration and insufficient component compatibility, which diminished the synergistic flame-retardant and smoke-suppressant effects. *(3)* The two-component systems with combined primer and topcoat application (PT2 and PT3) demonstrated excellent heat suppression performance, with their total heat release being reduced by 10.99% and 10.21%, resp., relative to the control group. PT2 (nano-SiO_2 /boric acid/borax) exhibited a favourable smoke suppression effect, with a 14.12% reduction in TSP, owing to the synergistic physical barrier effect between the silicate network formed by nano-SiO_2 and the boron-based glassy protective layer.

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