

Synergistic Flame Retardancy and Char-Forming Mechanism of Nitrogen-Modified Lignin/Melamine Cyanurate in Epoxy Resin

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Abstract

Nitrogen-modified lignin (Lig-N) was synthesized from alkali lignin by a one-pot grafting reaction with α -methylstyrene and N,N'-methylenebisacrylamide, and then combined with melamine cyanurate (MCA) to construct flame-retardant epoxy resin (EP) composites. Thermal stability, flammability, combustion behavior, char morphology, and mechanical properties were evaluated by thermogravimetric analysis, limiting oxygen index (LOI), UL-94 vertical burning, cone calorimetry, scanning electron microscopy, and mechanical testing. Lig-N alone reduced the maximum mass-loss rate by 29.6%, increased the char yield by 11.4 percentage points, increased the LOI by 4.0 percentage points, and improved the UL-94 rating from NR to V-2; however, melt dripping remained. Incorporation of MCA produced a pronounced synergistic effect. At a Lig-N/MCA mass ratio of 5:5, Lig-N/EP-MCA-3 showed the best fire performance: peak heat release rate and total heat release decreased by 80.1% and 73.9%, respectively, whereas peak smoke production rate and total smoke production decreased by 82.9% and 74.4%, respectively. The LOI increased by 11.4 percentage points, and the composite achieved UL-94 V-0 without melt dripping. Char-residue analysis indicates that Lig-N promotes condensed-phase charring, while MCA contributes gas-phase dilution and char expansion, jointly generating a compact protective barrier against heat and oxygen transfer. The Lig-N/MCA ratio also governed the mechanical response; Lig-N/EP-MCA-1 (7:3) provided the best mechanical performance. These results demonstrate that a Lig-N/MCA hybrid system can substantially improve the fire safety of EP while retaining practically acceptable mechanical properties.

Introduction

Epoxy resin (EP) is widely used in construction, electrical and electronic devices, transportation, and other high-performance applications because of its favorable mechanical properties, adhesion, and processability^[1, 2]. Its inherent flammability, however, creates a substantial fire-safety concern^[3, 4]. Effective flame-retardant modification should suppress heat and smoke release, delay fire growth, and thereby provide additional time for evacuation and emergency response. Conventional halogen-containing flame retardants are increasingly restricted because of their toxicity and environmental persistence^[5–7]. Consequently, renewable and low-toxicity feedstocks have attracted considerable attention as building blocks for environmentally benign flame-retardant systems.

Lignin, the second most abundant natural biopolymer after cellulose, is an attractive precursor for bio-based flame retardants because it is renewable, low in toxicity, and intrinsically char-forming^[8, 9]. Its aromatic structure and abundant phenolic hydroxyl, aliphatic hydroxyl, methoxy, carbonyl, and carboxyl groups provide both a carbon source and versatile sites for chemical modification^[10]. Nevertheless, unmodified lignin generally delivers limited flame-retardant efficiency and may require high loading, which can compromise composite processability and mechanical properties. Introducing phosphorus-, nitrogen-, sulfur-, or silicon-containing functionalities is therefore a useful route to improve its efficiency. For example, Li et al.^[11] developed a P/N/Si-containing synergistic flame-retardant system for lignin-

based epoxy resin, which enabled the composite to achieve a UL-94 V-0 rating and an LOI of 33.6%, accompanied by a 47.77% reduction in the peak heat release rate. Tian et al.^[12] prepared a lignin-based APP@AL core-shell intumescent flame retardant for rigid polyurethane foam, which significantly reduced the heat and smoke release of the composites. Lu et al.^[13] developed a lignin-based charring agent that simultaneously improved the flame retardancy and mechanical properties of epoxy resin. Furthermore, a bio-based P/N/S-containing flame retardant was synthesized for PLA, enabling the composite to achieve a UL-94 V-0 rating at an ultralow loading of 1.0 wt% while maintaining its mechanical properties^[14].

Despite this progress, several challenges remain for lignin-based flame-retardant systems. The charring ability of lignin alone is often insufficient to achieve high fire resistance at low additive loading, whereas high loading may deteriorate the processability and mechanical properties of the host polymer. In addition, flame retardants that act predominantly in either the gas phase or condensed phase may not provide sustained protection throughout combustion. Structural modification of lignin combined with a complementary co-additive is therefore a promising strategy to increase efficiency while integrating gas-phase inhibition with condensed-phase barrier formation.

Melamine cyanurate (MCA) is a halogen-free, nitrogen-rich flame retardant with good thermal stability. Upon heating, MCA undergoes endothermic decomposition and releases nonflammable gases, which dilute combustible volatiles and can promote expansion of the protective char layer; it therefore contributes primarily to gas-phase inhibition while supporting condensed-phase protection. In contrast, nitrogen-modified lignin (Lig-N) retains aromatic units and nitrogen-containing groups that favor aromatization, dehydration, and char formation during thermal exposure. Combining Lig-N with MCA is expected to couple the robust char-forming capacity of lignin with the gas-release and intumescent functions of MCA. Such complementarity may improve flame retardancy while allowing the Lig-N/MCA ratio to be tuned to balance fire safety and mechanical properties.

In this study, nitrogen-modified lignin (Lig-N) was synthesized from alkali lignin using ethyl acetate as the solvent, with α -methylstyrene and N,N'-methylenebisacrylamide as modifying agents and azobisisobutyronitrile as the initiator. Lig-N and MCA were subsequently incorporated into EP to prepare a series of flame-retardant composites with different Lig-N/MCA ratios. Their thermal stability, flammability, combustion behavior, char morphology, and mechanical properties were systematically assessed by thermogravimetric analysis, LOI, UL-94 vertical burning, cone calorimetry, scanning electron microscopy, and mechanical testing. The study further correlates composition with char formation and proposes the synergistic flame-retardant mechanism, providing a basis for the design of bio-based, halogen-free EP flame-retardant systems.

1 Experimental section

1.1 Materials

Table 1 lists the materials used in this study, together with their specifications, purities, and suppliers.

Table 1
Materials used in this study.

Material	Specification/Purity	Manufacturer
Alkali lignin (Lig)	Industrial grade	Anhui Zesheng Technology Co., Ltd., China
α -Methylstyrene (AMS)	LR	Shanghai Macklin Biochemical Technology Co., Ltd., China
N,N'-Methylenebisacrylamide (MBA)	AR	Tianjin Kermel Chemical Reagent Co., Ltd., China
Azobisisobutyronitrile (AIBN)	Industrial grade	Anda Jiacheng Chemical Reagent Co., Ltd., China
Ethyl acetate (EA)	AR, 99.5%	Tianjin Zhiyuan Chemical Reagent Co., Ltd., China
Bisphenol A epoxy resin (EP, E51)	Industrial grade	Nantong Xingchen Synthetic Material Co., Ltd., China
Diethylenetriamine (DETA)	AR	Nanchang Chenfang Adhesive Products Co., Ltd., China
Melamine cyanurate (MCA)	Industrial grade	Shandong Haiwang Chemical Reagent Co., Ltd., China

1.2 Experimental procedure

1.2.1 Synthesis of Nitrogen-Modified Lignin (Lig-N)

As illustrated in Fig. 1, Lig-N was synthesized by grafting functional monomers onto the lignin backbone. Alkali lignin served as the feedstock, while α -methylstyrene (AMS) and N,N'-methylenebisacrylamide (MBA) were introduced as functional monomers and azobisisobutyronitrile (AIBN) as the initiator. The detailed experimental procedure is shown in Fig. 2. Briefly, a certain amount of alkali lignin was dissolved in ethyl acetate to prepare a lignin solution with a concentration of 25.0 g/L, after which 5.0 g of AMS, 2.0 g of MBA, and 0.5 g of AIBN were added sequentially. The mixture was stirred for 30 min until homogeneous, heated at 93°C for 20 h, and then washed repeatedly with ethanol to remove residual reagents. The collected solid was dried in a vacuum oven at 75°C for 24 h to afford Lig-N as a light-gray powder.

1.2.2 Preparation of Flame-Retardant Epoxy Resin Composites

Table 2 lists the formulations of the flame-retardant EP composites. EP was preheated at 70°C, after which the prescribed amounts of Lig-N and MCA were added and mixed until a visually homogeneous dispersion was obtained. Diethylenetriamine (DETA) was then incorporated at an EP/DETA mass ratio of 9:1. The mixture was stirred thoroughly, degassed in an ultrasonic bath, poured promptly into silicone

molds, and cured at 60°C for 1 h in a vacuum oven. The cured specimens were subsequently conditioned at room temperature for 2 h before demolding and characterization.

Table 2
Formulations of neat EP and Lig-N/EP-MCA flame-retardant composites.

Sample	EP/mass%	DETA/mass%	Lig-N/mass%	MCA/mass%
EP	90	10	0	0
Lig-N/EP	81	9	10	0
Lig-N/EP-MCA-1	81	9	7	3
Lig-N/EP-MCA-2	81	9	3	7
Lig-N/EP-MCA-3	81	9	5	5

1.3 Characterization

Fourier Transform Infrared (FTIR) Spectroscopy were recorded using a Shimadzu IRTracer-100 FTIR spectrometer. The samples were prepared using the KBr pellet method. The spectra were collected with 16 scans at a resolution of 4 cm⁻¹ over the range of 400–4000 cm⁻¹.

Thermogravimetric Analysis (TGA) was performed using a Shimadzu DTG-60(AH) thermogravimetric analyzer under a nitrogen atmosphere. Approximately 5 mg of each sample was used for the measurements. The temperature was increased from 20 to 800°C at a heating rate of 20°C min⁻¹.

The tensile properties were measured using a GMT universal testing machine at a constant crosshead speed of 10 mm min⁻¹. The flexural properties were determined according to GB/T 9341 – 2008 using rectangular specimens with dimensions of 80 mm × 10 mm × 4 mm, prepared in self-fabricated epoxy resin molds. The support span was 64 mm, and the crosshead speed was 2 mm min⁻¹. Five specimens were tested for each formulation, and the average values were reported.

Cone calorimeter tests were performed using an FTT Cone Calorimeter (FTT0004) in accordance with the ISO 5660-1:2015 standard. The specimens were prepared with dimensions of 100 mm × 100 mm × 3 mm. During the test, a heat flux of 35 kW m⁻² was applied to evaluate the combustion behavior of the samples.

Vertical burning tests were conducted in accordance with GB/T 2408 – 2008 and IEC 60695-11-10:2003. The specimens were prepared with dimensions of 130 mm × 13 mm × 3 mm. The flammability performance was evaluated using a CZF-5 horizontal and vertical burning tester.

Limiting oxygen index (LOI) tests were conducted in accordance with GB/T 2406.3–2022 and ISO 4589-3. The specimens were prepared with dimensions of 150 mm × 10 mm × 3 mm. The LOI values were measured using an FTT Oxygen Index Analyzer (OL-1402072).

Scanning electron microscopy (SEM) was performed using a JSM-7800F field-emission scanning electron microscope (JEOL, Japan). The fractured surfaces of the samples were sputter-coated with a thin layer of gold prior to observation. The samples were observed at a magnification of 1000×, and the images were acquired at a resolution of at least 300 dpi.

2 Results and discussion

2.1 Structural Characterization of Lig-N

Figure 3 shows the FTIR spectra of alkali lignin (Lig), AMS, MBA, and Lig-N. The broad band of Lig at 3126–3646 cm^{-1} is assigned to the stretching vibrations of phenolic and aliphatic O–H groups. The bands at 2919 and 2981 cm^{-1} are attributed to the asymmetric and symmetric stretching vibrations of aliphatic C–H bonds in $-\text{CH}_2$ and $-\text{CH}_3$ groups, respectively^[15]. Compared with Lig, Lig-N exhibits additional characteristic bands at 3308 and 1415 cm^{-1} , which may be associated with functional groups introduced during the modification process^[16, 17]. The appearance of these characteristic bands is consistent with the proposed chemical modification of lignin, supporting the successful introduction of the corresponding functional groups. However, FTIR provides only qualitative evidence for the proposed structural modification.

2.2 Thermal stability

The thermal degradation behavior of neat EP and the Lig-N/EP-MCA composites was assessed by TG and derivative TG (DTG) analysis (Fig. 4). The characteristic temperatures at 5% mass loss ($T_5\%$), at the maximum mass-loss rate (T_{max}), the maximum mass-loss rate (DTG_{max}), and the char residue at 800°C are summarized in Table 3.

Table 3
TG parameters of neat EP and Lig-N/EP-MCA flame-retardant composites.

Sample	$T_5\%/^{\circ}\text{C}$	$T_{\text{max}}/^{\circ}\text{C}$	$\text{DTG}_{\text{max}}/(\% \text{ min}^{-1})$	Char residue/mass%
EP	327.9	370.6	1.15	8.7
Lig-N/EP	323.8	376.7	0.81	20.1
Lig-N/EP-MCA-1	277.9	390.7	0.60	21.9
Lig-N/EP-MCA-2	281.7	386.1	0.46	30.1
Lig-N/EP-MCA-3	282.4	383.1	0.45	32.5

Table 3 shows that Lig-N altered the thermal degradation pathway of EP. Relative to neat EP, Lig-N/EP exhibited a 6.1°C increase in T_{max} , a 29.6% decrease in DTG_{max} , and an 11.4 percentage-point increase in char residue. These changes indicate that Lig-N promotes condensed-phase carbonization and reduces

the intensity of the principal mass-loss event. The lower $T_5\%$ of Lig-N/EP should, however, be considered when interpreting the overall thermal response.

Addition of MCA produced a distinct two-stage thermal response. Compared with Lig-N/EP, all Lig-N/EP-MCA composites exhibited lower $T_5\%$, which is consistent with the earlier decomposition of MCA and the formation of volatile decomposition products. At the same time, MCA reduced DTG_{max} , increased T_{max} , and increased char residue, indicating that the main decomposition event was attenuated and delayed despite earlier onset of mass loss. This behavior is consistent with early dehydration and crosslinking reactions followed by enhanced char formation. Lig-N/EP-MCA-3 (Lig-N/MCA = 5:5) gave the most favorable balance: relative to neat EP, T_{max} increased by 12.5°C , DTG_{max} decreased by 60.9%, and char residue increased by 23.8 percentage points. Relative to Lig-N/EP, T_{max} increased by 6.4°C , DTG_{max} decreased by 44.4%, and char residue increased by 12.4 percentage points.

Overall, the TG results demonstrate that Lig-N enhances char formation, whereas MCA further suppresses the maximum mass-loss rate and increases the char residue. The combination therefore improves the high-temperature barrier-forming capacity of the EP matrix, although the lower $T_5\%$ of the MCA-containing systems indicates that initial thermal stability and char-forming efficiency should be considered together rather than inferred from a single parameter.

2.3 Flame-retardant properties

The flammability of the EP systems was evaluated by LOI, UL-94 vertical burning, and cone calorimetry.

As summarized in Table 4, Lig-N increased the LOI of EP by 4.0 percentage points and improved the UL-94 classification to V-2; melt dripping nevertheless persisted. MCA addition further improved the fire performance. Lig-N/EP-MCA-1 and Lig-N/EP-MCA-2 exhibited LOI values 1.6 and 3.8 percentage points higher than Lig-N/EP, respectively, and both achieved UL-94 V-1 without melt dripping. Lig-N/EP-MCA-3 (Lig-N/MCA = 5:5) showed the best performance, with an LOI increase of 7.4 percentage points relative to Lig-N/EP and 11.4 percentage points relative to neat EP, together with a UL-94 V-0 rating and no melt dripping. These results establish a clear composition-dependent synergy between Lig-N and MCA.

Table 4
LOI values and UL-94 ratings of Lig-N/EP-MCA composites.

Sample	LOI/%	UL-94	
		UL-94 rating	Melt dripping
EP	21.7%	NR	Yes
Lig-N/EP	25.7%	V-2	Yes
Lig-N/EP-MCA-1	27.3%	V-1	No
Lig-N/EP-MCA-2	29.5%	V-1	No
Lig-N/EP-MCA-3	33.1%	V-0	No

Figure 5 presents the heat-release and smoke-production curves from cone calorimetry, while Table 5 summarizes time to ignition (TTI), time to peak heat-release rate (tpHRR), peak heat-release rate (pHRR), total heat release (THR), peak smoke-production rate (pSPR), and total smoke production (TSP).

Table 5
Cone calorimetry data of neat EP and Lig-N/EP-MCA flame-retardant composites.

Sample	TTI/s	tpHRR/s	pHRR/(kW m ⁻²)	THR/(MJ m ⁻²)	pSPR/(m ² s ⁻¹)	TSP/m ²
EP	48	115	1314.6	117.0	0.41	27.0
Lig-N/EP	51	117	969.8	89.1	0.30	28.7
Lig-N/EP-MCA-1	52	136	599.1	67.5	0.15	18.9
Lig-N/EP-MCA-2	50	160	319.9	68.8	0.12	18.1
Lig-N/EP-MCA-3	56	148	261.6	30.5	0.07	6.9

Cone calorimetry confirms that Lig-N/MCA effectively suppresses the fire hazard of EP. Lig-N alone increased TTI by 3 s and decreased pHRR and THR by 26.2% and 23.8%, respectively, relative to neat EP. The MCA-containing formulations showed further decreases in pHRR and THR. The optimum formulation, Lig-N/EP-MCA-3, extended TTI by 8 s and decreased pHRR and THR by 80.1% and 73.9%, respectively, relative to neat EP. Relative to Lig-N/EP, its TTI was 5 s longer, while pHRR and THR were lower by 73.0% and 65.8%, respectively. The concurrent reduction in rate and total heat release indicates that the 5:5 formulation limits both fire growth and the cumulative heat output.

The observed reductions in heat release are consistent with the complementary functions of Lig-N and MCA^[18–20]. Lig-N provides an aromatic, char-forming component that can undergo dehydration and condensation during heating. MCA decomposes endothermically and releases nonflammable nitrogen-

containing species, thereby diluting combustible volatiles and promoting expansion of the char layer. Their combination favors the development of an expanded yet coherent char layer, which limits heat transfer and restricts the transport of oxygen and pyrolysis products. This interpretation is supported by the reduced pHRR and THR but should be considered together with the char-residue observations discussed below.

Smoke-release data show the same composition dependence. Lig-N decreased pSPR by 26.8% but slightly increased TSP, indicating limited smoke suppression when used alone. After MCA addition, both pSPR and TSP decreased. Lig-N/EP-MCA-3 showed the greatest suppression, with pSPR and TSP decreases of 82.9% and 74.4%, respectively, relative to neat EP. Relative to Lig-N/EP, the corresponding decreases were 76.7% and 76.0%. The substantial reduction in smoke release is consistent with the formation of a more continuous char barrier and gas-phase dilution by MCA decomposition products.

Overall, Lig-N and MCA exhibit a composition-dependent synergistic effect in EP. The 5:5 Lig-N/MCA ratio provides the most favorable balance for suppressing heat release, smoke production, and melt dripping, and is therefore the preferred composition when fire performance is the primary design objective.

2.4 Morphology and structure of char residues

Figure 6 shows the macroscopic and microscopic morphology of the char residues after cone calorimetry. Neat EP produced little residual char, whereas Lig-N/EP formed a char layer approximately 1 cm high. The Lig-N/MCA formulations generated more expanded char layers, with heights of approximately 4.5, 5.5, and 9 cm for the three compositions. The pores observed in these layers are consistent with the release of gaseous products during combustion. At the microscale, neat EP produced a loose residue with numerous pores, whereas Lig-N/EP-MCA-3 formed the most compact char layer with fewer pores and cracks. This morphology supports the proposed barrier function: a more continuous and compact char layer can restrict heat transfer and oxygen ingress. The compositional trend also agrees with the cone-calorimetry results, although direct chemical characterization of the char would be required to establish the detailed carbonization pathway.

2.5 Flame-retardant mechanism

The flame-retardant action of the Lig-N/MCA system can be rationalized by complementary gas-phase and condensed-phase processes^[21, 22] (Fig. 7). During heating, Lig-N promotes dehydration, aromatization, and carbonization, yielding a char layer that impedes heat transfer and oxygen diffusion. MCA decomposes endothermically and releases nitrogen-containing nonflammable gases, which dilute combustible volatiles and contribute to char expansion. The resulting expanded, coherent char layer acts as a physical barrier that limits the transport of oxygen and pyrolysis products. The 5:5 formulation provides the most favorable balance between char-forming capacity and gas generation, which explains its superior LOI, UL-94, heat-release, and smoke-suppression performance. The proposed mechanism is

inferred from the thermal, fire, and morphology data; gas-phase analysis and char-composition characterization would be needed to verify individual reaction pathways.

In summary, Lig-N and MCA improve the flame retardancy of EP through a coupled mechanism: Lig-N promotes condensed-phase barrier formation, while MCA provides gas-phase dilution and supports char expansion. The interaction of these processes reduces heat release, smoke production, and melt dripping.

2.6 Mechanical Properties Analysis

Figure 8 compares the tensile and flexural properties of neat EP and the flame-retardant composites. Incorporation of Lig-N reduced the tensile and flexural strengths by 13.0% and 10.2%, respectively, relative to neat EP, likely because of limited interfacial compatibility and local filler aggregation. Such heterogeneity can create stress-concentration sites and facilitate crack initiation under load.

MCA addition partly recovered the mechanical properties, but the effect depended on the Lig-N/MCA ratio. Relative to Lig-N/EP, Lig-N/EP-MCA-1 (7:3) showed increases of 8.8% in tensile strength and 6.2% in flexural strength, giving the best mechanical performance among the flame-retardant formulations. Lig-N/EP-MCA-2 (3:7) showed smaller increases of 3.6% and 3.1%, respectively. In contrast, Lig-N/EP-MCA-3 (5:5) showed decreases of 2.0% in tensile strength and 0.8% in flexural strength relative to Lig-N/EP. These results indicate that an MCA content that is beneficial for fire performance is not necessarily optimal for mechanical performance.

Overall, adjustment of the Lig-N/MCA ratio enables a trade-off between fire performance and mechanical properties. Lig-N/EP-MCA-1 is the preferred composition when mechanical performance is prioritized, whereas Lig-N/EP-MCA-3 is more suitable when maximum flame retardancy and smoke suppression are required.

3 Conclusions

The main conclusions of this study are as follows:

- (1) Lig-N was successfully synthesized by modifying lignin with α -methylstyrene and N,N'-methylenebisacrylamide and was combined with MCA to formulate halogen-free flame-retardant EP composites. This approach uses lignin as a renewable carbon source while introducing nitrogen-containing functionality and establishes a practical route for constructing bio-based flame-retardant EP systems.
- (2) Lig-N improved the thermal stability and flame retardancy of EP by promoting char formation, although it reduced the mechanical properties to some extent. MCA addition generated a marked synergistic effect with Lig-N, increasing thermal stability and flammability resistance while suppressing heat release, smoke production, and melt dripping. Lig-N/EP-MCA-3 (Lig-N/MCA = 5:5) delivered the best

fire performance, whereas Lig-N/EP-MCA-1 (7:3) provided the best mechanical performance. Thus, the Lig-N/MCA ratio offers a means to tailor the balance between fire safety and mechanical performance for different application requirements.

(3) The Lig-N/MCA system operates through complementary condensed-phase and gas-phase mechanisms. Lig-N promotes the formation of a dense, stable char layer that limits heat transfer and oxygen diffusion. MCA releases inert gases that dilute combustible volatiles and assists expansion and stabilization of the protective char. The combined action accounts for the lower heat and smoke release and the elimination of melt dripping observed for the optimized formulation.

In summary, the conversion of lignin into Lig-N, followed by its synergy with MCA, provides an effective strategy for improving the fire safety of EP. At a total flame-retardant loading of 10.0 wt%, the optimized composite achieved UL-94 V-0, demonstrating the potential of this bio-based hybrid system for high-efficiency, halogen-free flame-retardant modification of epoxy resins.

Declarations

Author Contribution

Yiding Jia: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Visualization. Yanying Xu: Supervision, Project administration, Contribution acquisition, Conceptualization, Writing – review & editing. Chao Lyu: Writing – review & editing, Project administration. Youqi Chen: Investigation, Methodology.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

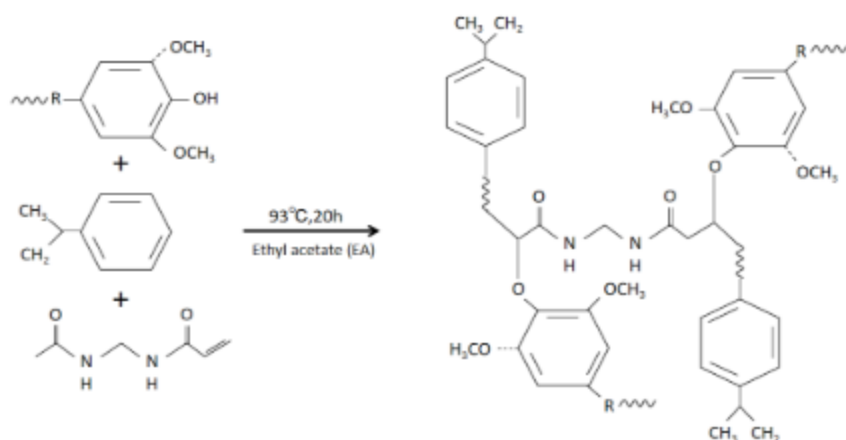


Figure 1

Schematic illustration of the synthesis route of Lig-N.

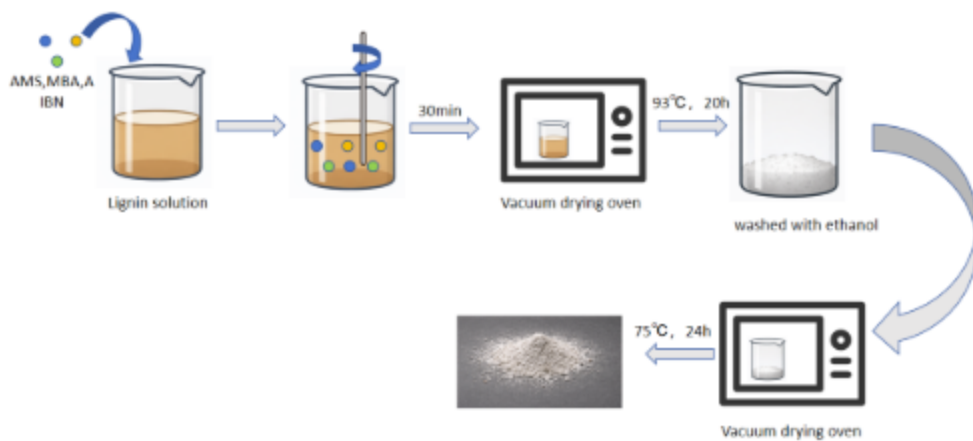


Figure 2

Schematic illustration of the preparation procedure of Lig-N.

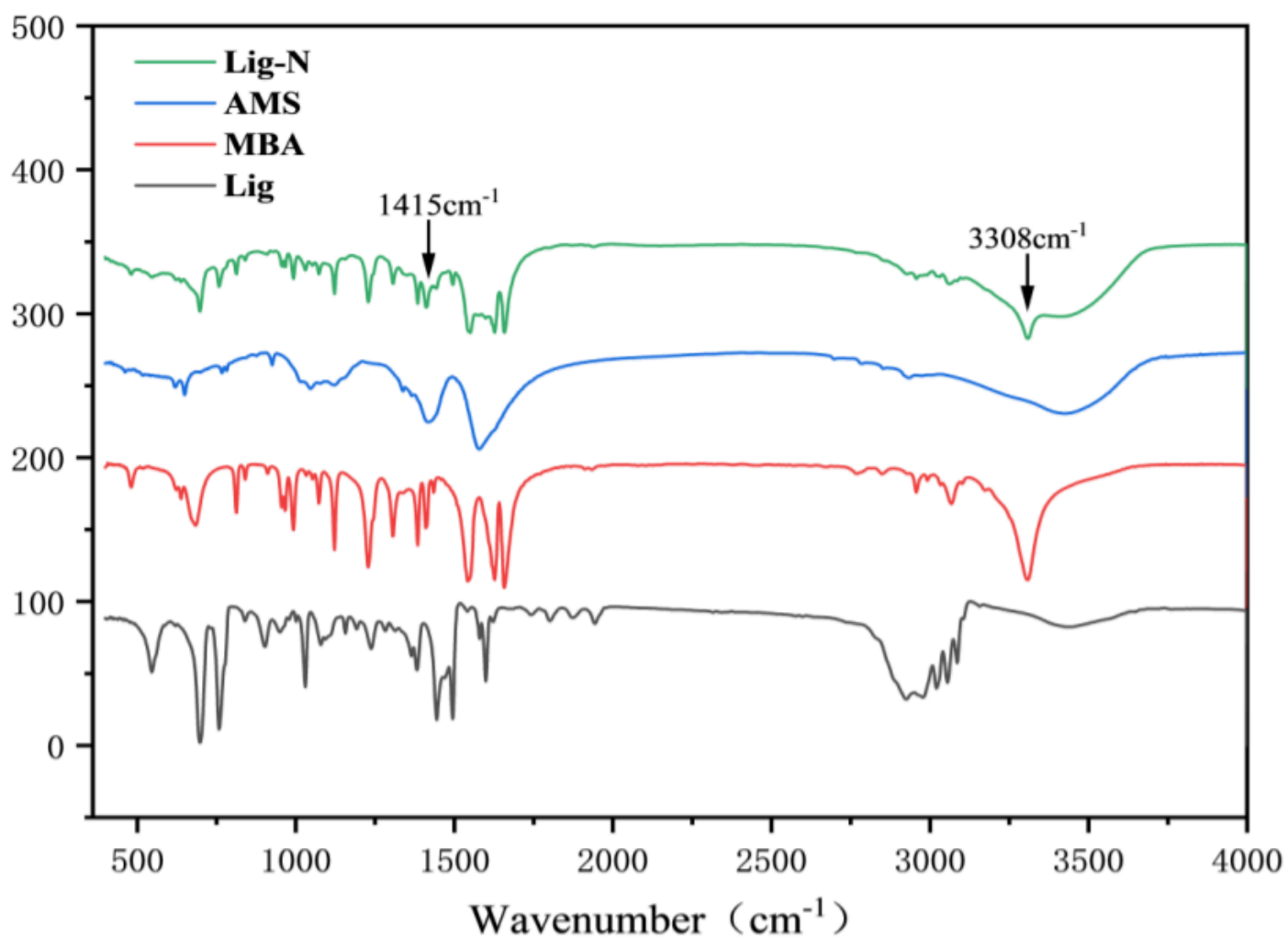


Figure 3

FTIR spectra of Lig, AMS, MBA, and Lig-N.

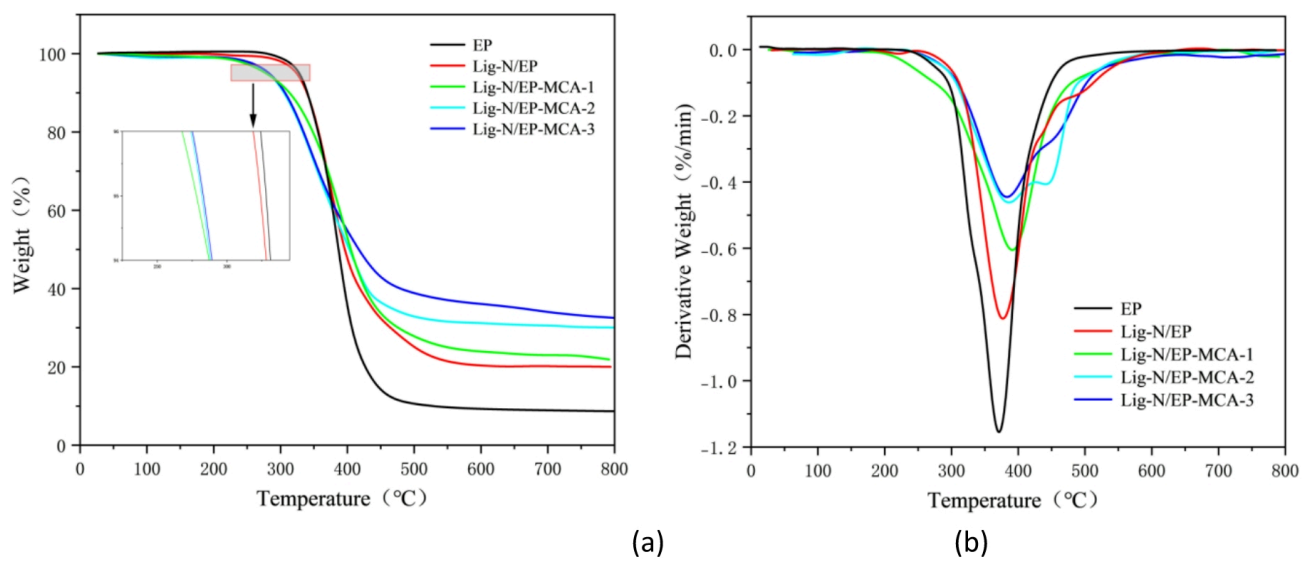


Figure 4

TG (a) and DTG (b) curves of neat EP and its flame-retardant composites.

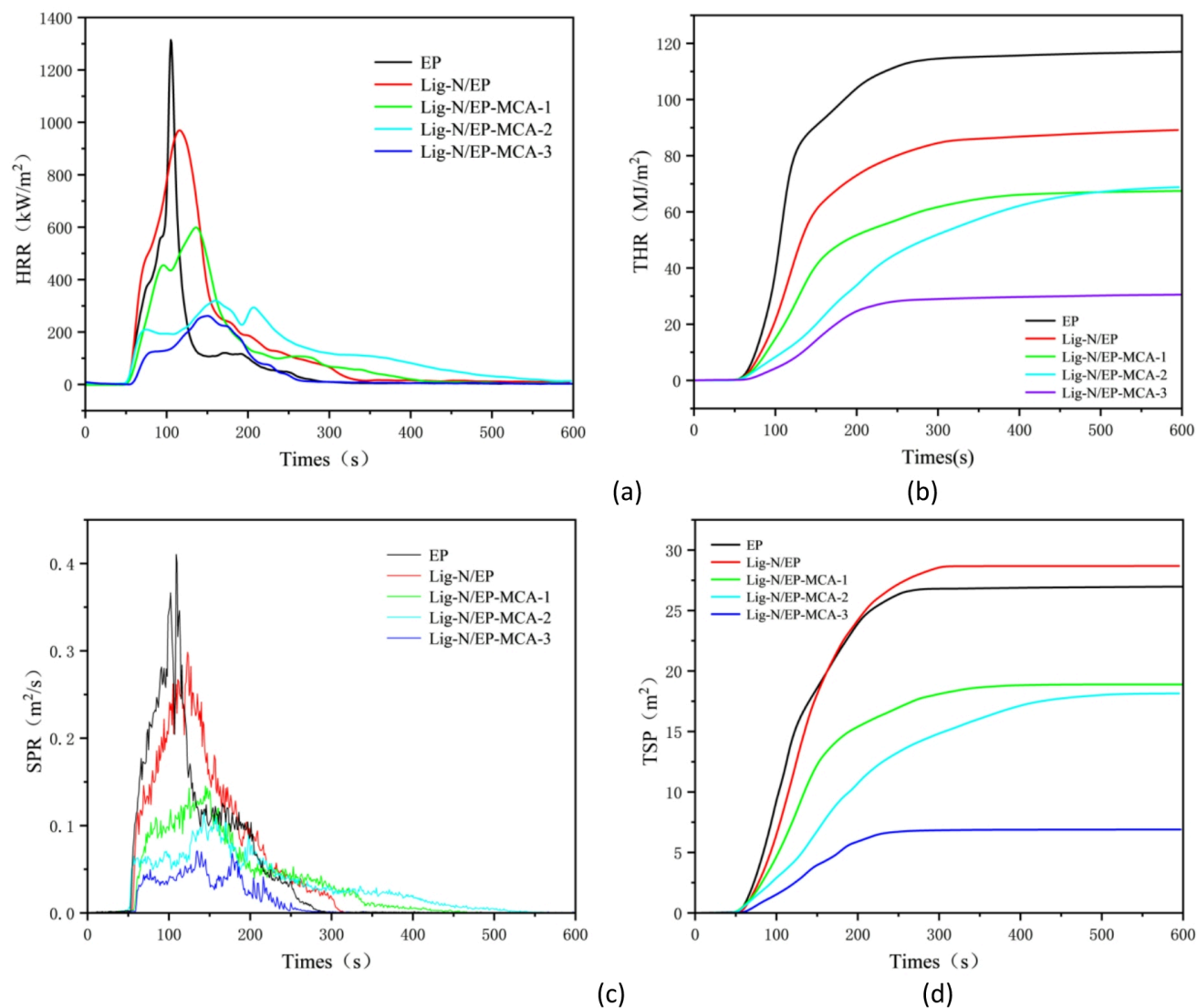


Figure 5

HRR (a), THR (b), SPR (c), and TSP (d) curves of neat EP and its flame-retardant composites.

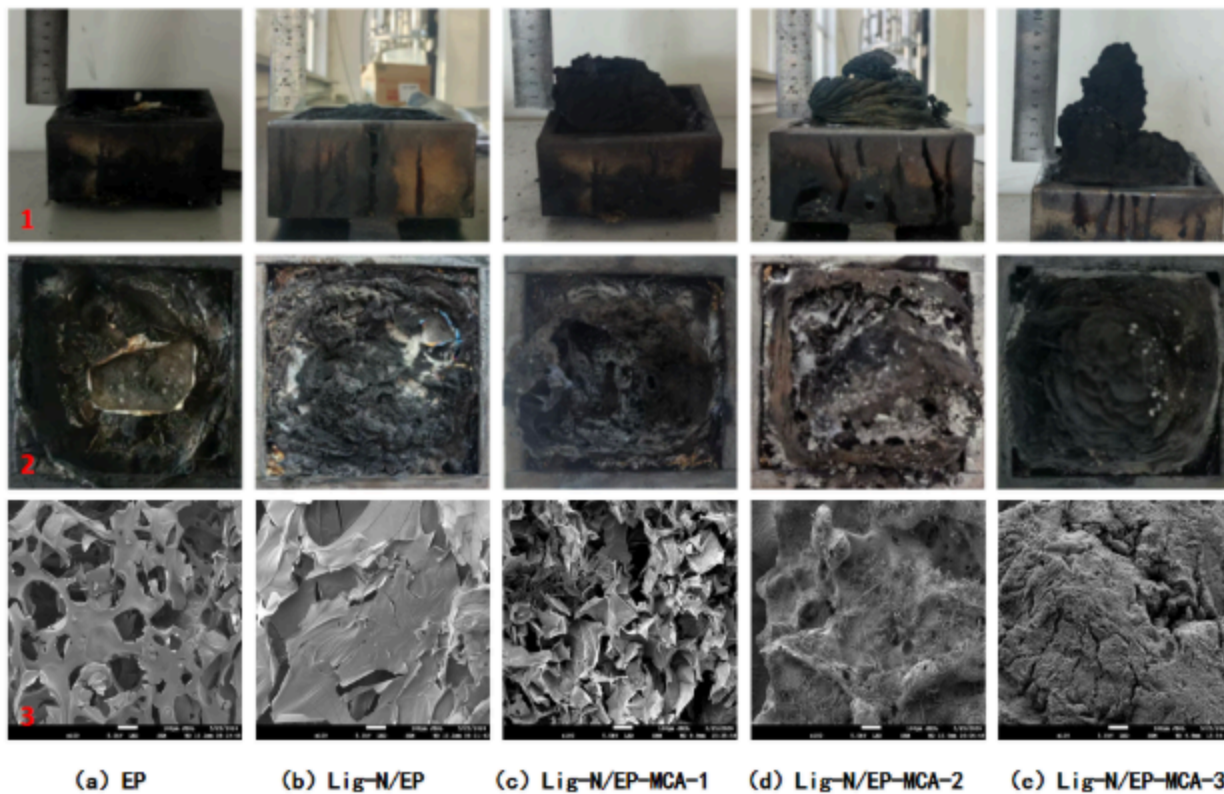


Figure 6

Digital images of char residues of neat EP and its flame-retardant composites after cone calorimetry.

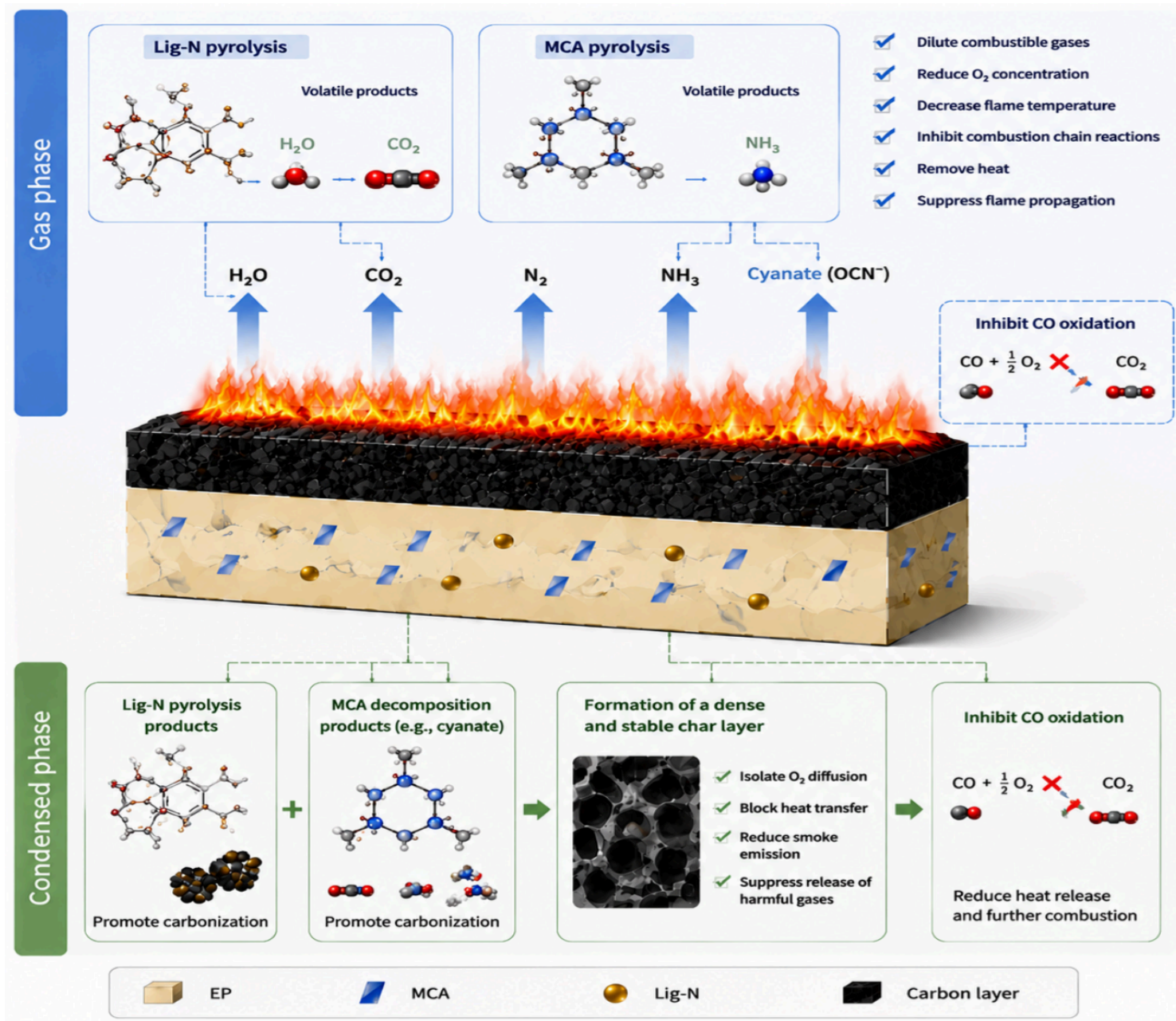


Figure 7

Schematic illustration of the flame-retardant mechanism of Lig-N/MCA in EP.

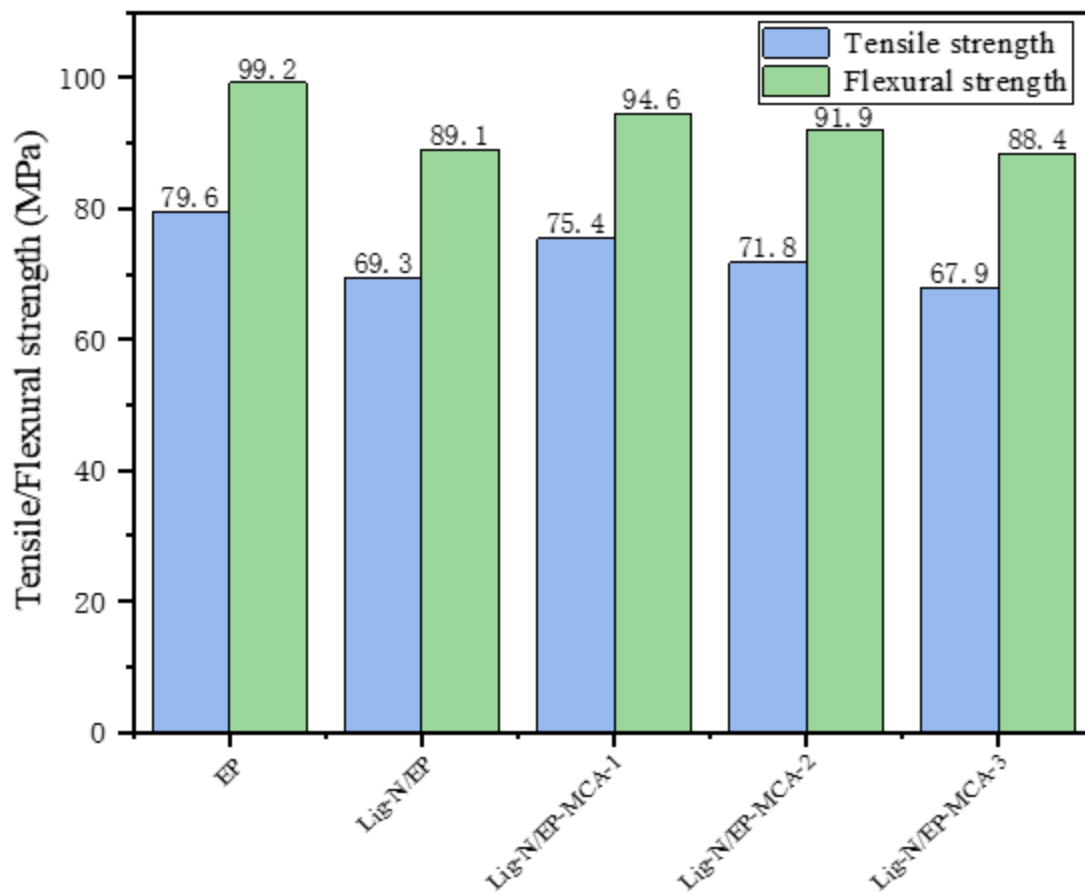


Figure 8

Mechanical properties of neat EP and Lig-N/EP-MCA flame-retardant composites.