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Glow-Wire Analysis of Polypropylene Blends for Mechanical and Marine Engineering Applications

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Abstract

Polymer materials are widely used due to their versatility; however, their vulnerability to fire is a significant concern, especially under electrical influences on engineered mechanical designs and marine structure applications. This study examines the fire resistance of a polypropylene (PP) blend using Glow-Wire Flammability Index (GWFI) and Glow-Wire Ignition Temperature (GWIT) tests. While previous research typically relies on flame-retardants to address flammability, this work proposes using a simple 1:1 weight ratio blend of two distinct PP types. This specific PP blend was selected to provide balanced material properties and improved processing consistency. The results from glow-wire tests were compared with previous findings to evaluate flammability performance. Our findings reveal that although the PP blend offers enhanced fire resistance compared to neat PP, it remains inferior to PP-containing flame-retardant additives. The outcomes suggest that this blended PP may be suitable for applications where mechanical properties, cost-effectiveness, and recyclability precede fire resistance, such as engineered automotive interiors, mechanical design of marine transportation, and low-risk electrical components in engineering infrastructure. This initial research contributes valuable insights into the fire behavior of PP blends. Moreover, it establishes a foundation for future investigations into polymer fire resistance, encouraging additional glow-wire testing on other polymer systems.

Keywords: Marine Structure; Engineered Design; Fire Accident; Glow-Wire Test; Polypropylene; GWFI; GWIT.

1. Introduction

Polymer materials such as polypropylene (PP), polyester, poly(butylene terephthalate) (PBT), poly(ethylene terephthalate) (PET), polyamide, acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) are widely used across various sectors. These include daily consumer goods, electronics, automotive, medical, maritime, aviation and aerospace, agriculture, and renewable energy. Recently, polymers, particularly in the form of composites, have gained attention as potential alternatives to traditional metal materials in marine applications, especially shipbuilding. Polymer

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composites offer notable advantages, including low weight, high strength-to-weight ratios, mechanical strength, chemical and environmental resistance, corrosion resistance, and flexibility in design [1-3].

In maritime structures, polymer composites have been applied in ship hulls, superstructures, radomes, sonar domes, railings, exhaust systems, propellers, rudders, bearings, shafts, turbine blades, and underwater components [4, 5]. Research into polymer composites for maritime use has been ongoing since shortly after World War II, notably by the US Navy during the Vietnam War. These early applications demonstrated that ships constructed with polymer composites are stiff, strong, durable, and easily repairable [6].

In fact, applying polymer composites instead of steel structures on ships can improve damage stability by reducing the weight of the upper part, thereby reducing the risk of collision and grounding. However, its flammability is contrary to international safety regulations (Safety of Life at Sea/SOLAS), so proper fire safety measures must be implemented to maintain safety and prevent accidents [7]. In practice, the risk of ship accidents is sometimes unavoidable, ranging from collisions, grounding, sinking, equipment failures, leaks, explosions, fires, or even terrorist attacks and piracy. There have been many studies, experimental and numerical, examining the strength of ship construction in several accident cases, such as collisions [8, 9], grounding [10, 11], ballistic weapons [12, 13], explosions [14], and fires [15-17].

Despite their advantages, ship accidents involving polymer composite structures continue to occur globally. Satriatama et al. [17] presented data on ship accidents from 2011 to 2020, revealing a consistent number of incidents caused by fire each year. An example is the fire accident involving KRI Klewang 625 in Banyuwangi, Indonesia, at the end of September 2012, illustrated in Figure 1. This 63-meter-long ship, built using carbon fiber reinforced polymer (CFRP), caught fire reportedly due to an electrical cable overheating. The ship's generators were not operational, requiring power to be supplied from shore connections. An electrical overload ignited the shore-side cable, and the fire spread rapidly onto the ship. The CFRP construction is believed to have contributed significantly to the quick propagation of the fire [18].

Figure 1. KRI Klewang 625 burned down at the end of September 2012 in Banyuwangi, Indonesia [19-22]

Highlighting the polymer materials used in the KRI Klewang 625, polymers have become essential materials in modern technology, extensively utilized in various forms, including composites, coatings, and fibers. Polymer materials, primarily when used in electrical equipment, pose two potential hazards: electrical shock and fire risk [23]. To address these hazards, the International Electrotechnical Commission (IEC) has introduced the glow-wire test, which evaluates the reaction of materials to fire risks during electrical product usage. This test is critical for assessing safety hazards associated with electrical appliances [24]. Türkan & Çetin [25] explained that the glow-wire test aims to prevent fires caused by overheating or electrically energized elements igniting plastic materials. The glow-wire test is a standardized method for evaluating the fire resistance of electrical insulating materials when exposed to heated wires, which could occur during short circuits [26, 27]. According to Duquesne et al. [28], glow-wire tests enable comparison of materials based on their flame-extinguishing properties and ability to avoid generating fire-spreading particles.

Responding to the need to evaluate polymer fire resistance in electrical applications, this study investigates the flammability characteristics of polypropylene (PP) blends using the Glow-Wire Flammability Index (GWFI) and Glow-Wire Ignition Temperature (GWIT) parameters. Flame-retardant additives are commonly employed to enhance the fire resistance of polymers, as reported extensively in previous studies [28–33]. However, this research uses a 1:1 weight ratio blend of two distinct types of PP without flame retardants. This specific ratio was chosen to achieve balanced mechanical properties and processing consistency, resulting in a homogeneous material structure. This helps ensure mechanical stability, minimizes segregation issues, and enhances reproducibility in manufacturing. Nonetheless, the fire resistance of this PP blend must be carefully assessed through glow-wire testing.

In this work, we compared our glow-wire test results with those from previous studies to better understand the flammability performance of our PP blend. The findings of this preliminary research are intended to contribute valuable insights into polymer fire characteristics, particularly for polypropylene, within the electrical industry.

2. Importance and Application of Glow-Wire

The glow-wire test is an essential fire-testing method used to simulate the occurrence of electrical short circuits. In this test, a glowing wire represents an electric arc resulting from a short circuit, generating significant heat that may ignite flammable materials. The glow-wire technique is widely used to evaluate the flammability characteristics of polymer materials commonly employed in electrical components [27]. The methodology and procedures for the glow-wire test are described comprehensively in the IEC 60695-2 standard series [34–37]. IEC 60695-2-10 [34] specifically details the apparatus and general procedures used during testing.

Glow-wire testing involves heating an element to a preset temperature ranging from 550 °C to 960 °C. The heated element is then pressed onto the specimen plate with a force of no more than 1 ± 0.2 N. The maximum penetration depth allowed is 7 ± 0.5 mm from the surface, and the contact time is maintained for 30 seconds. Observed temperature variations during testing can reach up to ±100 °C depending on the material tested. The heating element typically consists of a nickel-chromium (80/20) wire, approximately 4 mm thick, bent to form a tip with a radius of 1 cm. An example of a glow-wire testing apparatus is illustrated in Figure 2. The test apparatus is usually operated in a test chamber with a minimum volume of 0.5 m³ to maintain draft-free conditions. Additionally, the specimen should be placed at least 100 mm away from the chamber walls to ensure that oxygen depletion does not significantly influence the results.

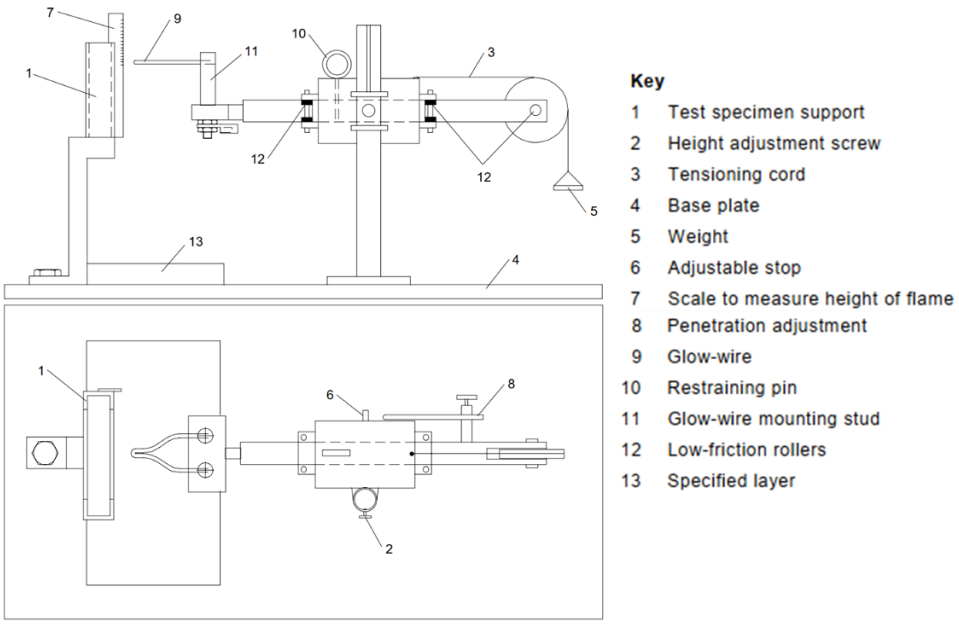


Figure 2. Schematic of the glow-wire testing apparatus based on IEC 60695-2-10 [34]

Glow-wire tests can be applied to both finished products and raw materials. IEC 60695-2-11 [35] explicitly addresses the glow-wire flammability test method for end-products (GWEPT). The glow-wire test provides two indices used to characterize material behavior: the Glow-Wire Flammability Index (GWFI) and the Glow-Wire Ignition Temperature (GWIT). According to IEC 60695-2-12 [36] and IEC 60695-2-13 [37], GWFI and GWIT results should not be the sole criteria for assessing fire hazards under actual fire conditions. However, these indices can significantly contribute to a comprehensive fire risk assessment relevant to specific applications.

GWFI is defined as the highest temperature at which the tested specimen either does not ignite or self-extinguish within 30 seconds after the glow-wire is removed. Additionally, the specimen must not cause the surrounding wrapping tissue to ignite at this temperature, nor should the specimen burn entirely [36]. GWIT is defined as 25 °C (or 30 °C if the test temperature is 960 °C) above the maximum temperature at which the specimen does not ignite or ignite for no longer than 5 seconds and does not fully burn [37].

Moreover, Acquasanta et al. [38] effectively illustrated the response of polymer materials under glow-wire test conditions, as depicted schematically in Figure 3. The penetration of the glowing wire creates three distinct regions within the polymer specimen:

- Pyrolysis Zone, where temperatures exceed the polymer's decomposition temperature.
- Melting Zone, characterized by the initial melting and slow degradation of the polymer material.
- Softening Zone, in which temperatures exceed the Heat Distortion Temperature, causing deformation without complete melting.

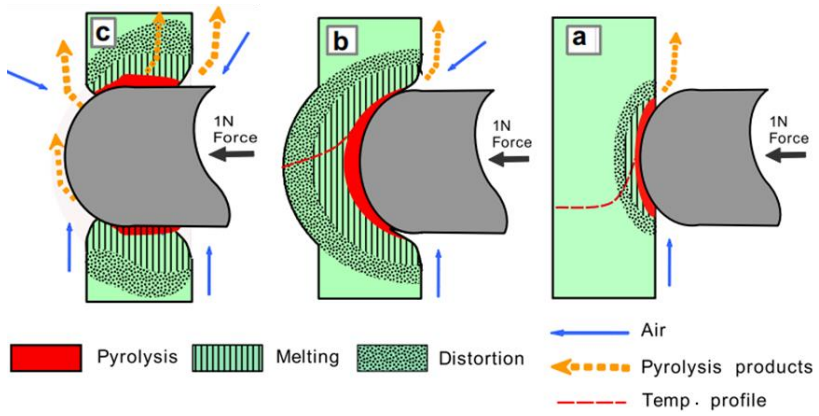


Figure 3. Response of polymer materials to glow-wire test [38]

Ignition occurs when gases released from the polymer's surface form a flammable mixture with air. The time until ignition depends on the polymer type and specimen thickness. The pyrolysis zone critically influences the test outcomes, although the mechanical and rheological properties of the polymer also significantly affect glow-wire test results [38].

3. Research Milestones in Past Decade

Polypropylene (PP) is among the fastest-growing thermoplastic commodities, exhibiting a market share growth of approximately 6–7% per year [39]. Despite its widespread use and numerous advantages, PP still exhibits poor fire-retardant properties [28, 30, 39]. Several studies have explored the flammability characteristics of polymeric materials, particularly PP, using the glow-wire testing method.

One of the earlier studies on glow-wire testing was conducted by Krämer & Blomqvist [29], who investigated the ignitability and combustion behavior of various plastics used in electrical equipment. The fabrication process for the PP specimens used by Krämer & Blomqvist [29] is illustrated in Figure 4. During their experiments, they observed the formation of a charcoal-like layer of mineral filler around the glow-wire. However, upon withdrawing the glow-wire after penetration, this charcoal layer and portions of the burning material detached from most specimens. The detached materials burned rapidly and flashed around the glowing wire. Ultimately, PP containing flame-retardant metal hydroxide achieved GWFI and GWIT ratings of 850/3.0, meeting the enclosure standards used in low-voltage switchgear and control equipment.

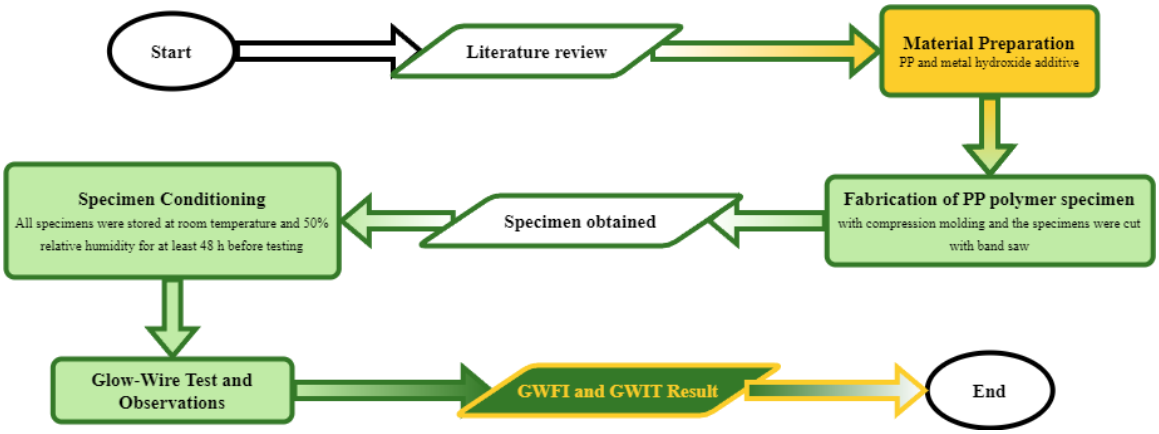


Figure 4. The PP specimen fabrication step from Krämer & Blomqvist [29]

In a subsequent study in 2008, Duquesne et al. [28] examined the impact of talc on the flame-retardant properties of highly filled intumescent PP composites. Talc is a non-flammable, non-explosive hydrated magnesium silicate with the chemical formula $Mg_3\ Si_4\ O_{1\ 0}\ (OH)_2$, as depicted in Figure 5. Duquesne et al. used PP7043-homopolymer combined with an intumescent flame-retardant additive, Exolit AP 765, and talc in their study. Exolit AP 765 is a commercially available non-halogenated flame-retardant that effectively enhances flame resistance through phosphorus/nitrogen synergism. Figure 6 illustrates the fabrication procedure for PP composites used by Duquesne et al. Their findings indicated that adding talc promoted the formation of magnesium phosphate. However, this magnesium phosphate weakened the protective intumescent charcoal layer's mechanical integrity, thereby reducing the flame retardant's effectiveness.

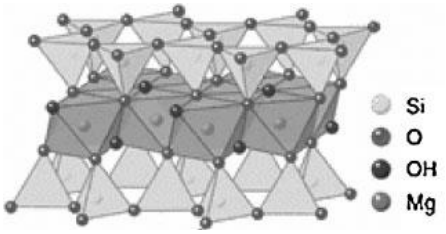


Figure 5. The lamellar structure of talc by Duquesne et al. [28]

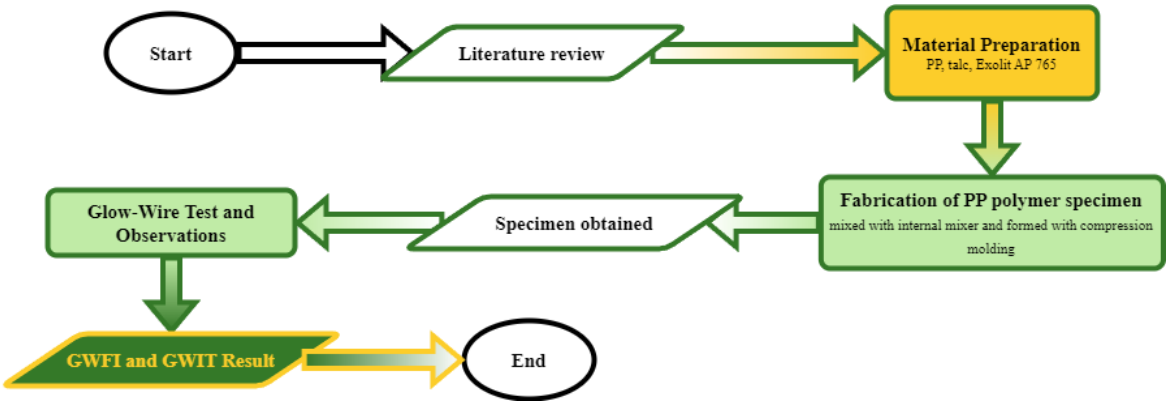
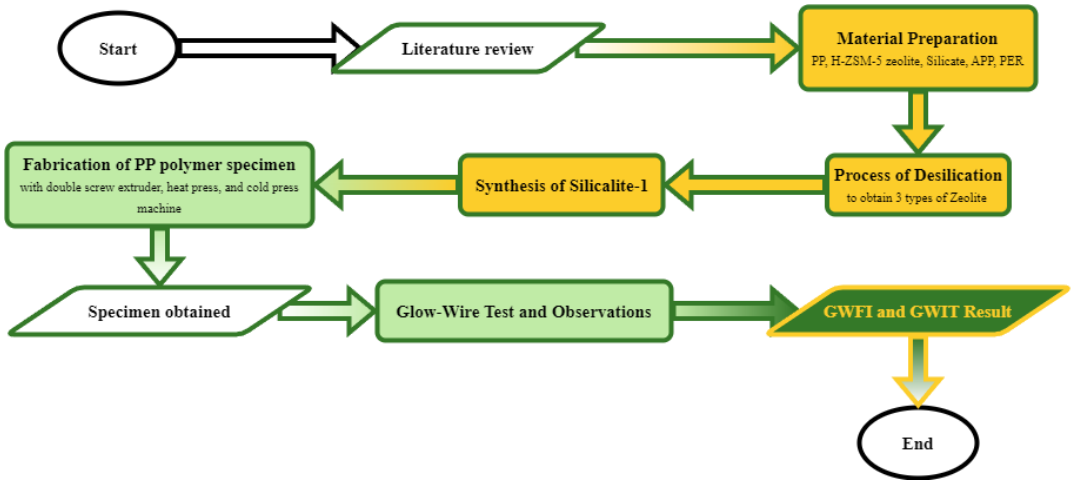
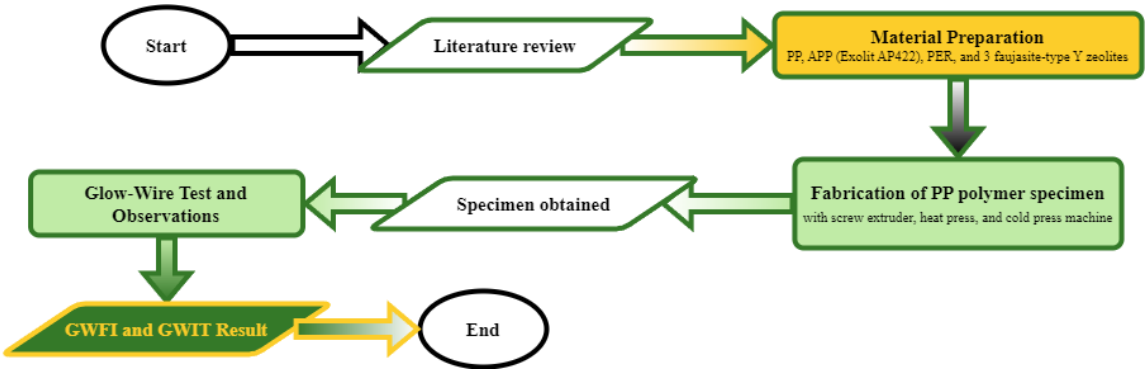


Figure 6. The PP composite fabrication step from Duquesne et al. [28]

In 2019 and 2020, Bernardes et al. [30] and Ribeiro et al. [31] conducted studies examining the synergistic effect of adding zeolite as a flame-retardant to polypropylene (PP). Both studies used PP type EP 448R but employed different types of zeolites. Bernardes et al. [30] utilized H-ZSM-5 zeolite, whereas Ribeiro et al. [31] used two variations of faujasite-type Y zeolite (sodic and acidic). The PP was combined with intumescent additives ammonium polyphosphate (APP) and pentaerythritol (PER) in both cases. The fabrication procedure for PP composites in these studies is illustrated in Figure 7. According to their glow-wire test results, zeolite effectively acted as a synergist for APP and PER, achieving a GWFI rating of 960 °C. Additionally, the combination of APP and PER facilitated the formation of a protective char phosphate ester layer, significantly enhancing the fire resistance of the PP composite.



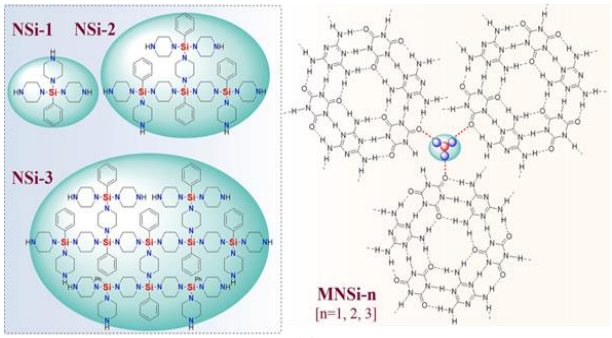
(a)



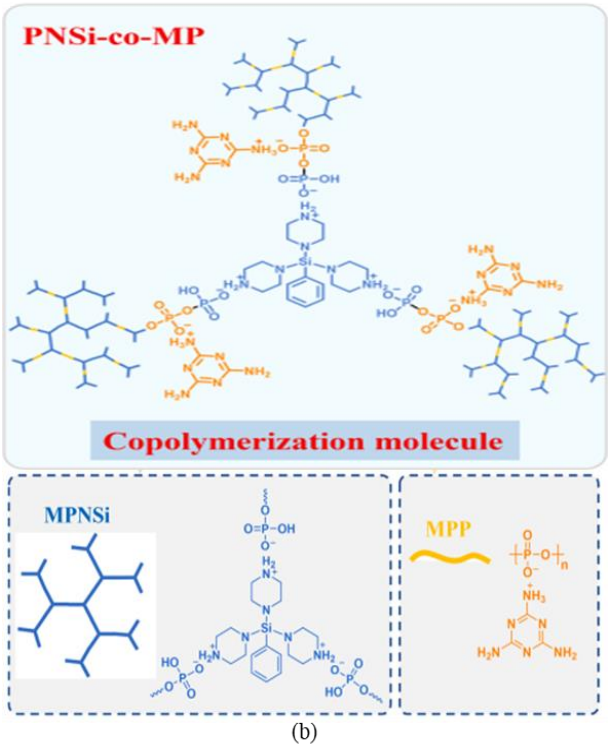
(b)

Figure 7. The PP composite fabrication step from: (a) Bernardes et al. [30] and (b) Ribeiro et al. [31]

More recently, Tang et al. [32, 33] conducted two related studies in 2023, exploring the effects of silicon-containing nitrogen flame retardants (NSi-n materials) on PP composites. Both studies used homopolymerized PP T30S, with differing formulations of NSi-n additives, as summarized in Figure 8. The PP composite fabrication processes for both studies, shown in Figure 9, were similar, with differences primarily in the synthesis methods of the NSi-n additives. In the first study, Tang et al. [32] synthesized NSi-n with melamine cyanuric acid (MCA) into MNSi-n and compared its performance against MCA alone. When blended with APP, the MNSi-n/APP mixture provided superior flame retardancy to the MCA/APP mixture, showing enhanced performance in terms of limiting oxygen index (LOI), GWFI, GWIT, and UL 94 V-0 ratings. This enhancement was attributed to the formation of a compact char layer rich in silicon and phosphorus.



(a)



(b)

Figure 8. The additive material molecules used as flame retardant materials: (a) Tang et al. [32] and (b) Tang et al. [33]

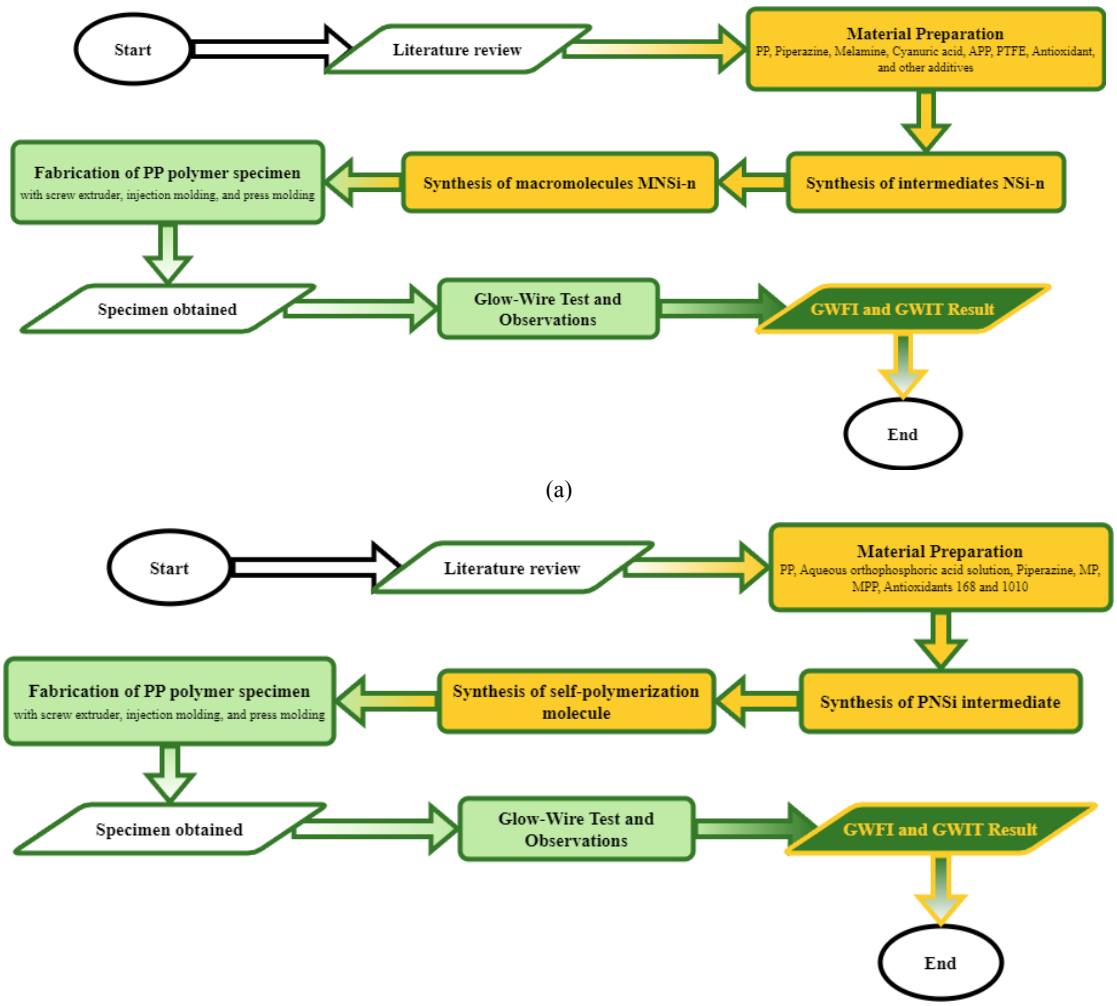


Figure 9. The PP composite fabrication step from: (a) Tang et al. [32] and (b) Tang et al. [33]

In the subsequent study, Tang et al. [33] synthesized a dendritic copolymer named PNSi-co-MP and evaluated its performance against a combined intumescent flame retardant (IFR) system containing MPNSi and MPP. The copolymer PNSi-co-MP exhibited superior flame-retardant performance across various tests compared to the MPNSi/MPP mixture. Specifically, the 12PNSi-co-8MP/PP formulation achieved a GWFI rating of 960/1.5 and GWIT rating of 875/1.5, whereas the 12MPNSi/8MPP/PP mixture only reached GWFI and GWIT ratings of 825/1.5.

Table 1 summarizes the key findings from the glow-wire tests mentioned above, highlighting the additives used and their impact on improving PP's flame-retardant properties. Generally, additives such as flame retardants are incorporated into PP to improve its inherently poor flame resistance, thus enhancing overall material safety.

Table 1. Summary of glow-wire testing research on PP materials in the last decade

Ref.	Research Subject	Additive Material	Key finding
Kramer & Blomqvist (2007) [29]	Fire behavior of plastics for electrical application	Metal hydroxide	The glow-wire tests showed inconsistent results for PP due to its tendency to form a char layer that can be rapidly removed from the specimen by molten material. While a char layer formation around the glowing wire was desirable, this layer was sometimes withdrawn, causing a rapid flame flash.
Duquesne et al. (2008) [28]	Influence of talc on the fire retardant properties of highly filled intumescent polypropylene composites	Exolit AP 765 Talc	Talc's influence on polypropylene in the glow-wire test modified how the material shrinks away from the hot wire. This alters the behavior of the intumescent layer and the test outcome. Formulations with at least 30% intumescent additives and 10% reinforcement talc filler content were necessary and successfully passed the glow-wire test
Bernardes et al. (2019) [30]	Synthesis and Application of H-ZSM-5 Zeolites with Different Levels of Acidity as Synergistic Agents in Flame-Retardant Polymeric Materials	APP PER Zeolite Silicate	The addition of the intumescent formulation enhanced the GWFI to 850 °C, and the addition of zeolites, regardless of acid site concentration and accessibility, increased the standard value to a maximum of 960 °C. It was observed that the expressive increase of the accessibility and concentration of acid sites, verified in the samples zeo2 and zeo3, augmented the GWIT, reaching the value of 875 °C

Riberio et al. (2020) [31]	Influence of the zeolite acidity on its synergistic action with a flame-retarding polymeric intumescent formulation	APP PER Zeolite (NaY, HY, HYdes)	The glow-wire test showed that zeolites with a higher concentration of moderate-strength acidic sites catalyze reactions more efficiently between ammonium polyphosphate (APP) and pentaerythritol (PER) in a polypropylene matrix. This leads to better flame-retardant properties by enhancing the formation of char precursors.
Tang et al. (2023) [32]	Small core of piperazine/silane aggregation initiate efficient charring flame retardant effect in polypropylene composites	PTFE Antioxidant MNSi-1 APP MCA	(MNSi-n/APP)/PP performed glow-wire flammable index and also exhibited a lower heat release rate. Comparatively, the melamine cyanurate macromolecule without NSi-n skeleton with APP only formed ineffective char layers and weaker flame retardancy
Tang et al. (2023) [33]	Dendritic copolymers from P-, N- and Si-based monomer and melamine phosphate generate thermal deformation toughening and a rapid charring flame retardant effect in polypropylene	PTFE PNSi-co-nMP MPNSi MPP (melamine polyphosphate)	In a glow-wire test at 875 °C, the composite containing 12PNSi-co-8MP/PP exhibited a smaller and shorter flame than the comparison material (12MPNSi/8MPP/PP), indicating a stronger flame-retardant property. The flame disappeared faster in this composite, and the charred layer was more effective in forming a protective barrier.

Furthermore, previous studies allow the compilation of a general glow-wire testing procedure for PP materials, as summarized in Figure 10. This procedure starts with a literature review, followed by material preparation, including synthesis or selection of flame-retardant additives. The next stage involves fabricating PP composites using techniques such as screw extrusion, roll milling, injection molding, or extrusion molding. Prepared specimens are then conditioned according to IEC 60695-2 standards [34–37], after which glow-wire testing is performed based on GWFI and GWIT criteria outlined in IEC 60695-2-10 [34]. Finally, the test concludes with obtaining GWFI and GWIT values for the evaluated PP specimens.

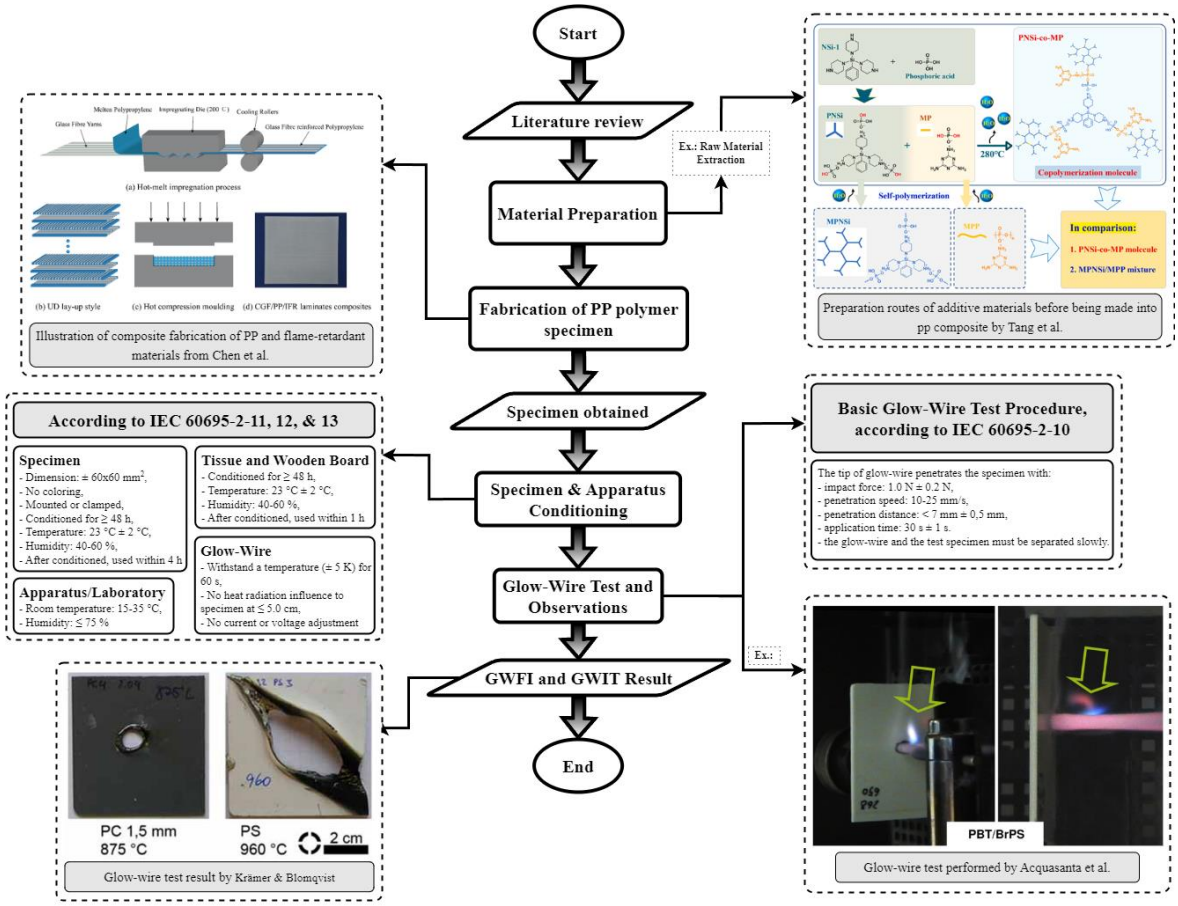


Figure 10. Basic glow-wire testing research procedure [29, 33-37, 40, 41]

4. Material and Methods

Glow-wire testing was performed at the Research Center for Testing Technology and Standards, National Research and Innovation Agency (BRIN), Tangerang, Indonesia. Testing was conducted using the ED&D GWT-200 Glow-Wire Tester, as illustrated in Figure 11. Polypropylene (PP) specimens provided by BRIN were used in this research, each having dimensions of 60×60×4 mm³. The specimens were composed of two different PP types combined in a 1:1 weight ratio: copolymer PP Samsung BJ 550 and homopolymer PP Titan Pro 6331. This ratio was selected to ensure structural homogeneity, improved mechanical stability, and reduced material segregation.

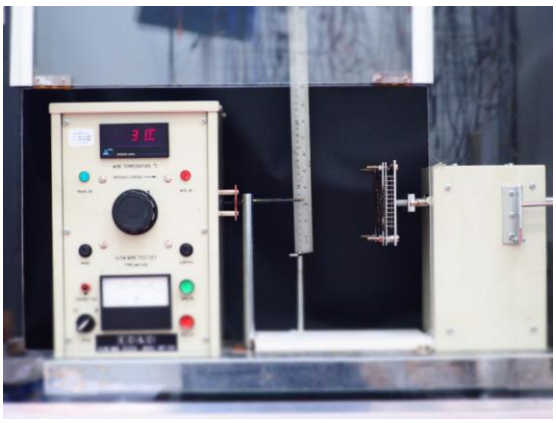


Figure 11. ED&D GWT-200 Glow Wire Tester Instrument

In this study, glow-wire tests were conducted to determine the GWFI and GWIT values of the PP blend. The general glow-wire testing procedure used is described previously in Section 2. According to IEC 60695-2-10 [34], specific criteria must be met by the glow-wire during testing. The glow-wire should maintain a constant temperature with a tolerance of ±5 K for at least 60 seconds. Furthermore, the glow-wire must not emit radiation affecting specimens positioned at least 5 cm away. Once testing begins, the current or voltage adjustments are not permitted until the test concludes.

Specimen conditioning and testing criteria for GWFI and GWIT follow IEC 60695-2-12 and IEC 60695-2-13 standards [36, 37]. Conditioning requirements differ slightly between specimens and test apparatus components. Specimens must be conditioned for at least 48 hours at a temperature of 23 °C ± 2 °C and relative humidity between 40% and 60%. After removing specimens from this environment, testing must be completed within four hours. Similarly, wrapping tissues and wooden boards must undergo the same conditioning (23 °C ± 2 °C, 40–60% humidity) for at least 48 hours and should be used within one hour after conditioning. Glow-wire tests are performed in laboratory conditions with ambient temperatures of 15–35 °C and maximum relative humidity of 75%. GWFI and GWIT procedures follow stepwise methodologies outlined in IEC standards. In GWFI testing, three specimens are exposed to an initial chosen temperature. If a specimen fails, the test is repeated at a temperature reduced by 50 K. Conversely, if all specimens pass, the temperature is increased by 50 K. This iterative process continues until the highest temperature at which all specimens meet the criteria is identified. GWIT testing employs a similar incremental temperature adjustment method, specifically assessing ignition resistance. Testing continues until the highest temperature is reached without specimen ignition. Once a failure occurs at a higher temperature, testing concludes.

In summary, the glow-wire tests performed in this research strictly adhere to the IEC 60695-2-12 (GWFI) and IEC 60695-2-13 (GWIT) standards, consistent with the general flowchart of glow-wire testing procedures presented in Figure 10.

5. Results and Discussion

5.1. Obtained Testing Data

The GWFI and GWIT tests were conducted on specimens made from a combination of two polypropylene (PP) materials. Table 2 summarizes the detailed glow-wire test results, including observations of phenomena at various test temperatures, recorded following IEC 60695-2-12 and IEC 60695-2-13 standards [36, 37].

Table 2. Summary of glow-wire test results on a combination of two PP materials

Temperature	Ignition (>5 s)	Ignition time after removal	Molten drip	Wrapping tissue burnt	Specimen consumed	Decision	
						GWFI	GWIT
550 °C ± 10°K	No	-	No	No	No	Pass	Pass
600 °C ± 10°K	No	-	No	No	No	Pass	Pass
650 °C ± 10°K	No	-	No	No	Partially	Pass	Pass
700 °C ± 10°K	No	-	No	No	Partially	Pass	Pass
750 °C ± 10°K	No	-	No	No	Partially	Pass	Pass
800 °C ± 15°K	Yes	26 s	Yes	No	Partially	Pass	Fail
850 °C ± 15°K	Yes	>30 s	Yes	Yes	Totally	Fail	Fail
Result						**800/4.0**	**775/4.0**

According to GWFI and GWIT standards, testing begins at a temperature within the 550–960 °C range and is incremented by 50 °C if specimens pass the required criteria. In this study, glow-wire tests commenced at 550 °C. Within the 550–750 °C temperature range, specimens consistently met GWFI and GWIT test criteria. Specifically, at 550 °C and 600 °C, specimens showed no ignition or dripping, and the glow-wire did not significantly consume the specimens. In the 650–750 °C temperature range, specimens did not ignite or drip; however, partial penetration and localized consumption of the specimens occurred. Figure 12 illustrates a representative result of the glow-wire test at 650 °C.

Figure 12. Final glow-wire test results at a test temperature of 650 °C

As the test temperature increased to 800 °C, the specimens exhibited significantly different behaviors compared to lower temperatures. At this temperature, ignition lasting more than 5 seconds occurred upon glow-wire penetration, accompanied by melting and dripping. However, the dripping was insufficient to ignite the wrapping tissue. After withdrawing the glow-wire, the specimen continued to burn for approximately 26 seconds but did not burn entirely. Thus, the specimen met GWFI criteria but failed GWIT criteria at 800 °C due to sustained ignition during glow-wire penetration. Consequently, the GWIT value was determined as 775/4.0. Figure 13 illustrates the ignition phenomenon observed at 800 °C.

Figure 13. Final glow-wire test results at a test temperature of 800 °C

Subsequently, the test temperature was raised by an additional 50 °C to 850 °C to establish the GWFI value. At this temperature, the specimen ignited immediately upon glow-wire penetration, burned continuously for more than 30 seconds after wire removal, melted significantly, and the resulting drips ignited the wrapping tissue. The specimen completely burned out, as depicted in Figure 14, making further testing impossible. Based on these findings, testing concluded that the PP blend achieved satisfactory flame resistance with final values of GWFI: 800/4.0 and GWIT: 775/4.0, summarized in Table 2.

Figure 14. Final glow-wire test results at a test temperature of 850 °C

5.2. Comparison with the Pioneer Work

To clearly evaluate the flammability characteristics of polypropylene (PP), it is essential to compare the current experimental results with those of previous pioneering studies. In our research, PP specimens were created by combining two PP types—PP Samsung BJ 550 (copolymer) and PP Titan Pro 6331 (homopolymer)—at a 1:1 weight ratio. By

contrast, earlier studies typically used neat PP or PP blends with various flame-retardant additives to improve fire resistance. For comparison purposes, pioneering studies were selected based on clear PP compositions, the presence of GWFI and GWIT test data, and the explicit use of glow-wire testing. Table 3 provides a detailed summary of GWFI and GWIT values from both the current study and previous research on PP materials with and without flame-retardant additives.

Table 3. GWFI and GWIT values in current research and pioneer research

No.	Data Sources	Additive Materials Composition	Glow-Wire Result	
			GWFI (˚C/mm)	GWIT (˚C/mm)
1	Current experiment	• No additive • Contains two PP materials, 50% PP Samsung BJ 550 + 50% PP Titan Pro 6331	800/4.0	775/4.0
2	Kramer & Blomqvist [29]	• Metal hydroxide	850/3.0	850/3.0
3	Duquesne et al. [28]	• 35% of Exolit AP 765	960/3.0	875/3.0
4		• 35% of Exolit AP 765 • 30% of talc	960/3.0	825/3.0
5	Bernardes et al. [30]	• No additive (neat)	650/7.0	700/7.0
6		• 30% of APP and PER (3:1)	850/7.0	800/7.0
7		• 3% of Zeolite1 • 30% of APP and PER (3:1)	960/7.0	850/7.0
8	Riberio et al. [31]	• No additive (neat)	700/7.0	725/7.0
9		• 30% of APP and PER (3:1)	960/7.0	875/7.0
10		• HY zeolite • 30% of APP and PER (3:1)	960/7.0	960/7.0
11	Tang et al. [32]	• 1% of PTFE and antioxidant	725/3.0	750/3.0
12		• 22% of MNSi-1 + APP	825/3.0	775/3.0
13	Tang et al. [33]	• 1% of PTFE	625/1.5	650/1.5
14		• 20% of PNSi-co-nMP • 1% of PTFE	960/1.5	875/1.5
15		• 12% of MPNSi • 8% of MPP • 1% of PTFE	825/1.5	825/1.5

To facilitate more straightforward interpretation, GWFI and GWIT values from our study and selected pioneering studies are plotted in Figure 15. Our PP combination (represented at point 1) yielded GWFI and GWIT values of 800 °C and 775 °C, respectively. In contrast, neat or minimally modified PP materials (only 1% additives, points 5, 8, 11, and 13) exhibit GWFI values between 625–725 °C and GWIT values between 650–750 °C. PP blends with flame-retardant additives achieved notably higher GWFI and GWIT values, typically ranging from 825 °C up to the maximum test temperature of 960 °C.

The graphical representation (Figure 15) clearly shows two distinct clusters:

- A group without significant additives (blue ellipse) that exhibits lower GWFI and GWIT values, indicating limited fire resistance.
- A flame-retardant additive group (red ellipse) that demonstrates higher but more variable GWFI and GWIT values, reflecting enhanced fire resistance.

The combined PP material tested in our study (highlighted in green) falls between these two groups, suggesting intermediate performance. This indicates that combining two PP types without flame-retardant additives provides better fire resistance than neat PP but does not achieve the consistently higher thermal performance of flame-retardant formulations.

In addition, trendline analysis was performed on GWFI and GWIT data from the pioneering study. For neat PP material with a 1% additive, the trendline follows the Equation 1, $y = 218.96 + 0.73x$, with an R^2 value of 0.85919, as shown in Figure 16. This high R^2 value indicates a strong positive correlation between GWFI and GWIT, suggesting that an increase in GWIT reliably leads to a corresponding increase in GWFI. The close fit of the trendline to all data points confirms the uniformity of the dataset, as all samples share the same base material with minimal additive content.

This trendline analysis also highlights that even with a small amount of additive, neat PP exhibits a relatively predictable improvement in thermal resistance. However, since this material lacks flame-retardant additives, its fire resistance remains limited, making it unsuitable for high-temperature applications where enhanced flame resistance is required.

$$y = 218.96 + 0.73x \quad (1)$$

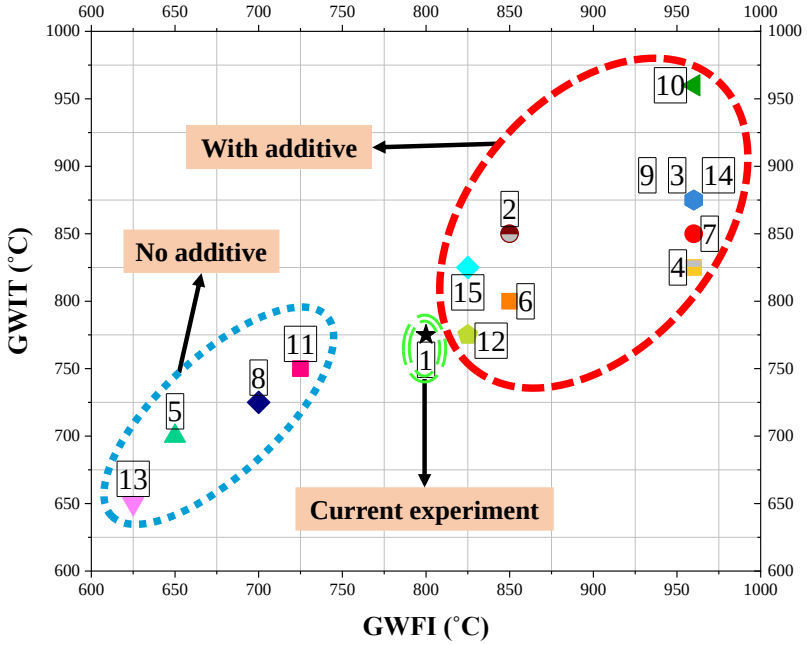


Figure 15. Graph of GWFI and GWIT values for several PP materials in the study

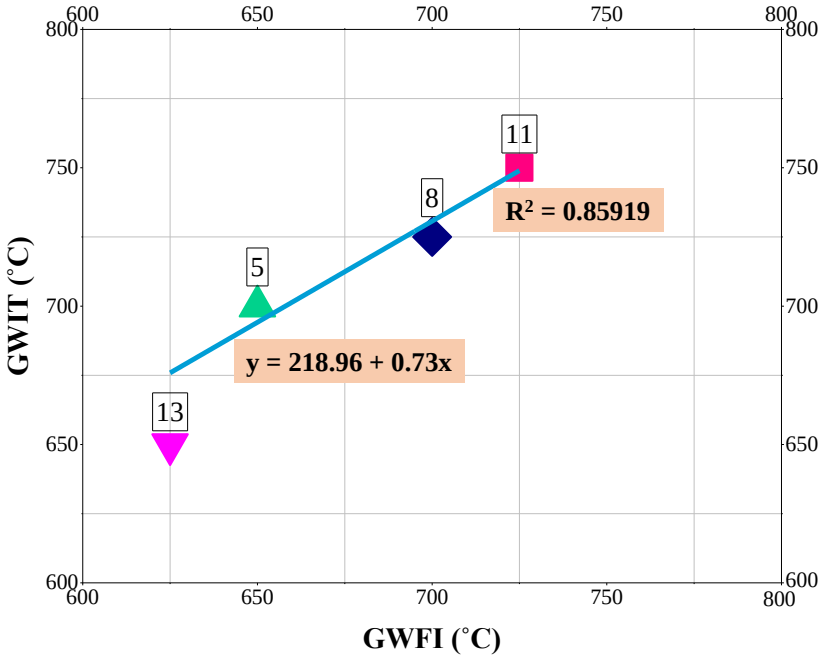


Figure 16. Trendline of GWFI and GWIT data on neat PP material (1% additive)

In the GWFI and GWIT data, which use PP material with flame-retardant additives, the trendline is shown in Figure 17. The trendline follows the Equation 2, y = 687.22 + 0.18x, has a much lower slope than that of neat PP, and the R^2 value of 0.14825 indicates a weak correlation between GWFI and GWIT. An R^2 value close to 0 suggests that the data is sporadic, which is expected since the dataset consists of PP materials with different types of flame-retardant additives. This variability may be due to differences in flame-retardant formulations and material composition. While flame-retardants enhance fire resistance, they introduce complexities that make statistical correlations less reliable compared to neat PP.

$$y = 697.22 + 0.18x \quad (2)$$

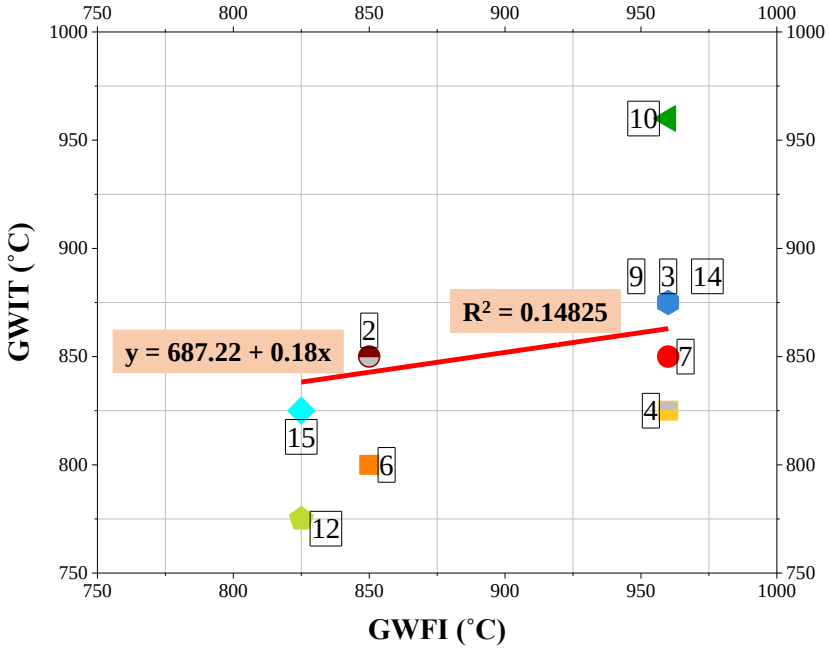


Figure 17. Trendline of GWFI and GWIT data on PP material with flame-retardant additives

Nevertheless, within Figure 17, specific data points appear close to the trendline, suggesting certain PP additive combinations yield more consistent thermal performance. These include PP blends with: Metal Hydroxide (data 2), 35% Exolit AP 765 (data 3), 3% Zeolite1 and 30% APP + PER (3:1) (data 7), 30% APP + PER (3:1) (data 9), 20% PNSi-co-nMP and 1% PTFE (data 14), and 12% MPNSi + 8% MPP + 1% PTFE (data 15). The GWFI and GWIT data for these compositions share a similar inclination, suggesting that certain additive combinations contribute to a more predictable thermal performance.

The linear regression model shown in Figure 17 indicates a weak correlation between GWFI and GWIT, with an R^2 value of 0.14825. To better understand the relationship between these two parameters, especially in materials with varying formulations, alternative fitting models such as polynomial and exponential regression are considered. Figure 18 presents a comparison of these models. The second-order polynomial and exponential regressions improve the fit, with an R^2 value of 0.21431. A significant improvement is seen with the fourth-order polynomial, which yields an R^2 value of 0.99824. This sharp increase suggests that the relationship between GWFI and GWIT in flame-retardant PP materials is highly nonlinear. The nonlinearity may result from the complex interactions and synergistic effects of the various flame-retardant additives used in the formulations.

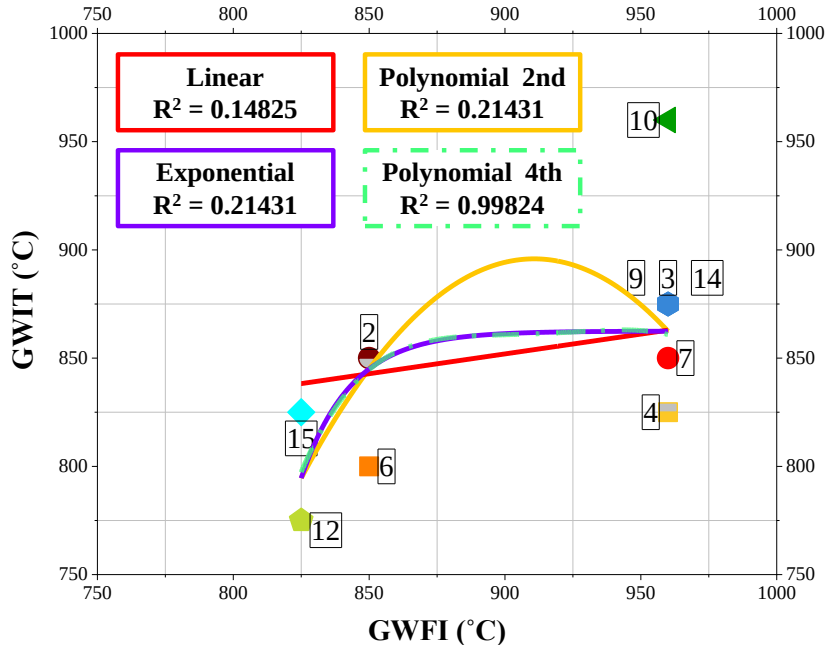


Figure 18. Trend-line model variation of GWFI and GWIT data on PP material with flame-retardant additives

By applying and comparing different regression models, the variability in the dataset can be addressed more effectively. This approach improves the interpretation of the results and offers more reliable insights into material performance. However, due to the complexity and diversity of flame-retardant systems, developing a single predictive model that applies to all cases remains challenging.

6. Conclusions

This study evaluated polypropylene (PP) fire resistance performance using glow-wire testing, comparing current investigation results with previous pioneering studies' results. Unlike prior studies, which typically employed flame-retardant additives to enhance the flammability resistance of polymers, this research focused on a simple blend of two PP materials without additional flame retardants. Specifically, copolymer PP Samsung BJ 550 and homopolymer PP Titan Pro 6331 were mixed at a 1:1 weight ratio. This particular ratio was chosen to achieve balanced properties, ensuring that both polymer types contributed evenly to the mechanical and physical characteristics of the blend. Additionally, the equal ratio provided excellent processing consistency simplified the blending procedure, and facilitated the creation of a homogeneous and mechanically stable structure, reducing segregation and improving manufacturing reproducibility.

The effectiveness of this PP blend was measured using the Glow-Wire Flammability Index (GWFI) and Glow-Wire Ignition Temperature (GWIT). Results from glow-wire tests demonstrated that the blended PP achieved respectable values of GWFI: 800/4.0 and GWIT: 775/4.0. To better understand these findings, a comparative analysis was performed against data from previous studies involving neat PP and PP composites with flame-retardant additives. The resulting GWFI-GWIT plot clearly illustrated the intermediate performance of the current PP blend, placing it above neat PP materials with minimal or no additives but distinctly below those containing flame-retardant additives. This position indicates that combining two PP types significantly improves fire resistance compared to neat PP. However, it does not reach the higher thermal stability exhibited by flame-retardant-enhanced composites.

The tested PP blend's moderate flame resistance makes it suitable for applications where mechanical properties, affordability, processability, and recyclability are more critical than fire resistance. Such applications include automotive interiors, packaging, consumer goods, and low-risk electrical insulation components. The absence of flame-retardant additives also supports recyclability, an advantage typically compromised when flame retardants are included.

Ultimately, this study represents preliminary research that lays the groundwork for future investigations. Additional research is planned to conduct extensive glow-wire and fire behavior assessments on a broader range of polymer materials, enabling comprehensive evaluations of their flammability characteristics and performance under realistic application scenarios.

7. Declarations

7.1. Author Contributions

Conceptualization, H.F., I.S., N.K., I.K., I.I., and Q.L.; methodology, H.F., I.S., A.A.P., A.R.P., and R.W.; software, A.A.P., H.I.A., and F.I.; validation, H.F., I.S., N.K., I.K., Q.L., and E.P.B.; formal analysis, A.A.P., H.I.A., and F.I.; investigation, H.F., I.S., A.A.P., A.R.P., and I.Y.; resources, H.F., I.S., N.K., I.K., and Q.L.; data curation, A.A.P. and A.R.P.; writing—original draft preparation, A.A.P., A.R.P., I.I., and E.P.B.; writing—review and editing, A.A.P., A.R.P., I.Y., and R.W.; visualization, A.A.P., H.I.A., and F.I.; supervision, H.F., I.S., A.A.P., and A.R.P.; project administration, H.F. and A.R.P.; funding acquisition, A.R.P., I.I., and R.W. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

Data sharing is not applicable to this article.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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