

## Mini-Review

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# Impact of ionic liquids on the thermal properties of polymer composites

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**Abstract:** The integration of ionic liquids and polymer composites has become a promising way to improve their thermal properties, representing a notable advancement in the development of advanced materials for specific applications. Their thermal properties heavily influence the suitability of polymer composites for particular applications. It is imperative to understand and manipulate the thermal behavior of these composites to optimize their performance across various fields. In this mini-review, diverse polymer matrices and fillers utilized in polymer composites containing ionic liquids are categorized. Additionally, various ionic liquids employed in studies related to the thermal properties of polymer composites are identified. The impact of ionic liquids on the thermal properties of these composites is also briefly reviewed. The knowledge illustrated in this review enriches the understanding of the types of polymer matrices and fillers used in conjunction with ionic liquids, as well as their thermal properties. In a nutshell, imidazolium-based ionic liquids with tetrafluoroborate, bis(trifluoromethylsulfonyl)imide, hexafluorophosphate, halides, and hydrogen sulfate anions have the impact of improving the glass transition temperature, melting temperature, degradation temperature, and thermal conductivity of thermoplastic, thermosetting, and elastomer composites.

**Keywords:** ionic liquid, glass transition temperature, melting temperature, degradation temperature, thermal conductivity

## 1 Introduction

The integration between ionic liquids and polymer composites has emerged as a promising opportunity for enhancing their thermal properties, marking a significant stride in the pursuit of advanced materials with tailored applications. Ionic liquids have gained prominence as versatile additives in polymer composites due to their exceptional characteristics, such as non-volatility, good thermal stability, low toxicity, and tunable physicochemical properties (1,2). Ionic liquids bring a myriad of functionalities to polymer composites (3). The solvation properties of ionic liquids enable them to serve as efficient plasticizers, enhancing the flexibility and processability of the composite materials (4). Ionic liquids also act as effective dispersing agents, promoting homogeneity and preventing agglomeration of fillers within the polymer matrix. This dispersion control positively impacts mechanical properties, such as tensile strength and modulus, by ensuring a uniform distribution of reinforcing materials (5). Furthermore, the inherent tunability of ionic liquids allows for the customization of polymer composites with desired electrical conductivity (6), opening possibilities for applications in conductive materials and electroactive devices (7,8). Additionally, their non-volatility and low toxicity make them environmentally friendly alternatives, addressing sustainability concerns in the preparation of biodegradable fibers and composites (9,10). In recent years, ionic liquids have garnered substantial interest for their potential as compatibilizing agents for polymer blends (11).

The thermal properties of polymer composites play a crucial role in determining their suitability for specific applications. Understanding and manipulating the thermal behavior of these composites are imperative for optimizing their performance in various fields. The thermal properties of polymer composites encompass a broad spectrum, ranging from specific heat capacity to thermal diffusivity and

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conductivity (12,13). These properties significantly influence the material's ability to maintain dimensional stability, resist thermal degradation, and dissipate heat under varying temperature conditions. Achieving an optimal balance between thermal insulation for thermal stability and thermal conductivity for efficient heat transfer is a critical challenge in composite design. Consequently, extensive research efforts have been directed toward exploring novel strategies to enhance and fine-tune the thermal performance of polymer composites (14). The thermal properties of polymer composites include crucial parameters such as glass transition temperature, melting temperature, degradation temperature, and thermal conductivity. The glass transition temperature delineates the transition from a rigid to a more flexible state. Melting temperature signifies the phase transition from a solid to a liquid state, while degradation temperature marks the onset of polymer breakdown (15). Thermal conductivity is essential for efficient heat transfer. These parameters collectively define the thermal behavior of polymer composites and are central to their applicability in diverse technological domains.

In this context, the integration of ionic liquids emerges as an encouraging probability, offering unique prospects to customize the thermal behavior of polymer composites with precision and efficiency. Ionic liquids act as versatile modifiers that can be strategically integrated with polymer composites (16,17). Their distinctive properties enable precise control over vital thermal parameters, such as glass transition temperature, melting temperature, degradation temperature, and thermal conductivity (18,19). This strategic integration not only opens chances for designing composites with tailored thermal profiles but also enhances the whole thermal performance of the composites, addressing specific application requirements across a spectrum of industries. To date, within the purview of the authors' knowledge, scant reviews have been undertaken exclusively dedicated to reviewing the polymer matrices, fillers, ionic liquids, and thermal properties of polymer composites containing ionic liquids. Therefore, this mini-review explores the multi-functional role played by ionic liquids in polymer composites, specifically focusing on their impact on thermal properties. The intricate interplay between ionic liquids and composite components holds the key to unlocking novel pathways for improving the overall thermal performance of polymer composites. By exploring the impact of ionic liquids, this review aims to provide an inclusive understanding of the underlying means governing the thermal behavior of these composite materials.

## 2 Polymer matrices used for polymer composites containing ionic liquids

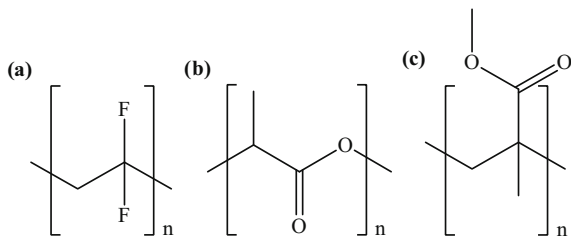
Polymer matrices serve as the foundation for polymer composites, and their selection plays a critical role in determining the overall performance and applicability of the resulting materials. Among the diverse matrix options for polymer composites containing ionic liquids, thermoplastics, thermosetting polymers, and elastomers stand out for their exclusive characteristics and versatility (20–22). Thermoplastics have the ability to undergo reversible melting and reshaping processes, offering excellent processability and recyclability (23). Thermosetting polymers, on the other hand, provide enhanced mechanical strength and dimensional stability through irreversible curing reactions (24). Elastomers contribute flexibility and resilience, making them suitable for applications requiring elasticity. The integration of ionic liquids into these matrices introduces an additional layer of complexity, influencing parameters such as thermal and mechanical properties. The compatibility between the polymer matrix and ionic liquid is also crucial, as it affects the interaction within the composite (25,26). Furthermore, the wise choice of the polymer matrix allows for tailoring the thermal properties of the composite, presenting opportunities for applications in the field of advanced materials.

### 2.1 Thermoplastic matrices used for polymer composites containing ionic liquids

Research into polymer composites containing ionic liquids has identified several thermoplastic matrices commonly utilized in such systems. Table 1 shows examples of thermoplastic matrices used for polymer composites containing ionic liquids. It can be observed that poly(vinylidene fluoride) (PVDF), polylactide (PLA), and poly(methyl methacrylate) (PMMA) are typically used as thermoplastic matrices in polymer composites containing ionic liquids. Figure 1 shows the chemical structures of PVDF, PLA, and PMMA. PVDF has an exceptional reputation in polymer research owing to its unique piezoelectric properties and excellent mechanical strength, making it suitable for applications in sensors and actuators (8). PLA is derived from renewable resources and combines biodegradability with commendable mechanical properties, catering to eco-friendly applications (25). PMMA

**Table 1:** Examples of thermoplastic matrices used for polymer composites containing ionic liquids

Thermoplastic matrix	Abbreviation	References
Fluoro-ethylene-propylene	FEP	(20)
High-density polyethylene	HDPE	(28,29)
Polyamide 6	PA6	(30,31)
Polyaniline	PANI	(32)
Polycaprolactone	PCL	(33)
Polyetheretherketone	PEEK	(4)
Polyetherimide	PEI	(34)
Poly(3,4-ethylenedioxythiophene)	PEDOT	(35)
Poly lactide	PLA	(10,18,25,33)
Poly(methyl methacrylate)	PMMA	(14,27,36,37)
Polypropylene	PP	(30,38,39)
Poly(vinyl chloride)	PVC	(40)
Poly(vinylidene fluoride)	PVDF	(7,8,41–44)
Thermoplastic polyurethane	TPU	(45)

**Figure 1:** Chemical structures of (a) PVDF, (b) PLA, and (c) PMMA.

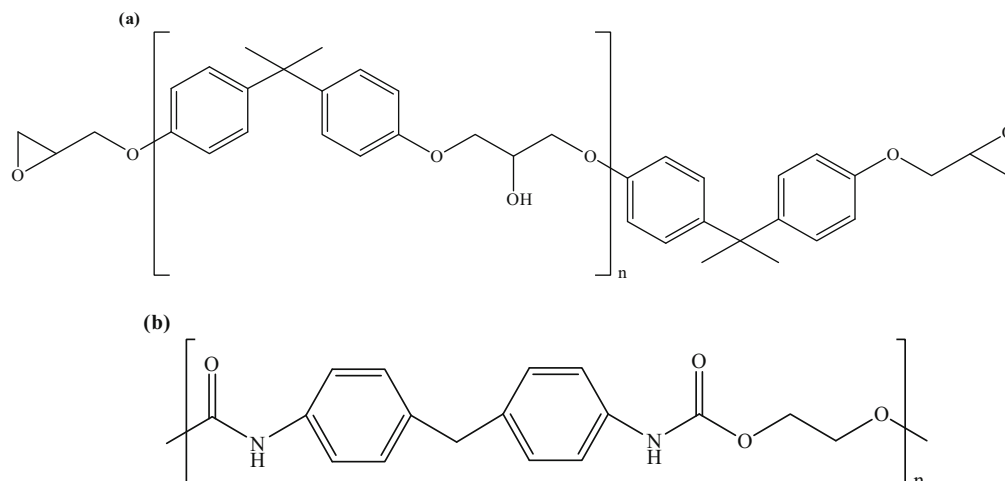
has good optical transparency, impact resistance, and ease of processing, offering utilization in diverse sectors, including optic devices (27). The thermoplastic nature of these matrices facilitates a facile processing route, allowing for the formation of complex shapes and structures. The integration of ionic liquids into these thermoplastic matrices unfolds ways for innovative solutions in fields such as sensor technologies, sustainable materials, and transparent electronics. The resulting composites not only inherit the inherent properties of the thermoplastic matrix but also benefit from the tunable characteristics imparted by the ionic liquid. This collaborative integration exemplifies the adaptability and potential of thermoplastic matrices in engineering advanced polymer composites. In conclusion, the cooperative integration of ionic liquids with thermoplastic matrices like PVDF, PLA, and PMMA demonstrates their adaptability and potential in developing sophisticated polymer composites, offering innovative solutions across diverse fields, including detection systems, eco-friendly materials and see-through electronics, thus exemplifying a versatile approach to material design and application development.

## 2.2 Thermosetting polymer matrices used for polymer composites containing ionic liquids

The selection of appropriate thermosetting polymer matrices is crucial for the development of polymer composites containing ionic liquids. Table 2 shows examples of thermosetting polymer matrices used for polymer composites containing ionic liquids. It can be seen that epoxy resin (EP) and polyurethane (PU) are repeatedly used compared to other thermosetting polymers. They play an important role in the preparation of polymer composites containing ionic liquids. Figure 2 shows the chemical structures of EP and PU. EP has extraordinary adhesive strength and resistance to chemical degradation and is a top candidate for applications demanding high-performance composites (46). PU possesses changeability and tailorable properties, excellent rigidity and flexibility, and thermal insulation (15). Thus, EP and PU offer unique composites with robust mechanical properties and chemical stability. The cross-linking nature of thermosetting polymers ensures a stable composite structure, rendering them suitable for automotive components and structural materials. The integration of ionic liquids into these thermosetting matrices introduces an additional dimension to their performance, critical for enhancing thermal conductivity and flame retardancy properties (12). This tactical integration of thermosetting polymer matrices and ionic liquids underscores the potential of these composites in tackling diverse challenges across various high-tech areas. The cooperation between the thermosetting matrix and ionic liquids creates materials with superior thermal and mechanical characteristics, expanding the scope for ground-breaking solutions in materials science. In conclusion, the strategic integration of thermosetting polymer matrices, particularly EP and PU, with ionic liquids not only enhances the thermal and mechanical properties of the resulting composites but also expands their potential for addressing multifaceted challenges in high-tech applications, exemplifying

**Table 2:** Examples of thermosetting polymer matrices used for polymer composites containing ionic liquids

Thermosetting polymer matrix	Abbreviation	References
Epoxy resin	EP	(12,17,19,21,46–51)
Flexible polyurethane	FPU	(52)
Polyimide	PI	(53)
Rigid polyurethane	RPU	(15,54,55)
Unsaturated polyester resin	UPR	(56)



**Figure 2:** Chemical structures of (a) EP and (b) PU.

the versatility and promise of these materials in materials science.

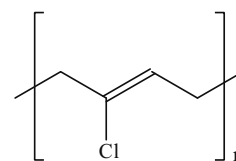
### 2.3 Elastomer matrices used for polymer composites containing ionic liquids

The investigation into elastomer matrices for polymer composites containing ionic liquids is also elucidated. Table 3 shows examples of elastomer matrices used for polymer composites containing ionic liquids. It can be perceived that polychloroprene (CR) emerges as a predominant elastomeric matrix in comparison to other elastomers, suggesting it is the preferred matrix for the preparation of polymer composites containing ionic liquids. The notable usage of CR is attributed to its inherent polarity, a characteristic derived from the presence of chlorine atoms

within its molecular chain structure (1). Figure 3 shows the chemical structure of CR. The integration of ionic liquids into the CR matrix resulted in composite materials with enhanced thermal stability and superior mechanical properties (57,58). The deliberate integration of ionic liquids into the CR matrix contributes to the development of composites with tailored mechanical properties, resilience, and thermal characteristics. This versatility expands the utility of such materials across assorted fields, as they can be tailored to meet specific industrial requirements. Moreover, the intentional integration between CR and ionic liquids emphasizes the potential for creating advanced materials capable of addressing the evolving needs of sundry industrial sectors. This strategic tactic not only augments the performance of elastomer composites but also signifies a proactive approach toward designing materials that can meet the dynamic demands of contemporary applications. In conclusion, the intentional integration of ionic liquids into the CR matrix exemplifies a strategic approach toward enhancing the mechanical resilience, thermal stability, and tailored properties of elastomer composites, underscoring their potential for meeting diverse industrial needs and signaling a proactive stance in materials design to address evolving application requirements.

**Table 3:** Examples of elastomer matrices used for polymer composites containing ionic liquids

Elastomer matrix	Abbreviation	References
Ethylene-vinyl acetate	EVM	(16)
Hydrogenated carboxylated nitrile butadiene rubber	HXNBR	(13)
Hydrogenated nitrile butadiene rubber	HNBR	(13)
Natural rubber	NR	(22)
Nitrile butadiene rubber	NBR	(59)
Polychloroprene	CR	(1,57,58,60–62)
Styrene butadiene rubber	SBR	(6)



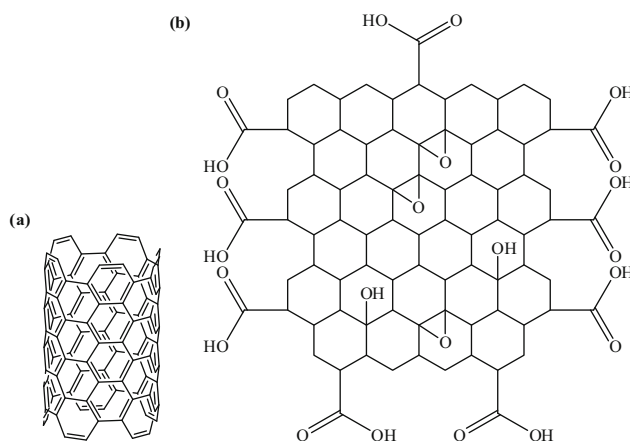
**Figure 3:** Chemical structure of CR.

### 3 Fillers utilized for polymer composites containing ionic liquids

Fillers can shape the specific properties of polymer composites. Amidst the various choices of fillers for polymer composites containing ionic liquids, carbon-based, inorganic-based, metal-based, and organic-based fillers contribute to tailoring mechanical, thermal, and electrical characteristics. Carbon-based fillers, like graphene and carbon nanotubes, are renowned for their exceptional strength and electrical conductivity (27,41), making them ideal for reinforcing the composites and enhancing their electrical properties. Inorganic-based fillers, such as ammonium polyphosphate (APP) and boron nitride nanosheets, offer improvements in thermal stability, flame-retardant performance, and thermal conductivity (19,47). Metal-based fillers, exemplified by metal–organic frameworks or nickel ferrite, contribute to enhanced flame retardancy and electrical conductivity (21,32). Organic-based fillers, including melamine and wood flour, provide organic reinforcement, making them crucial for applications in thermal insulation or biodegradable materials. The planned integration of these fillers with ionic liquids further amplifies their impact on the composite's properties, creating materials with multi-functional capabilities. The synergies between the stated fillers and the ionic liquids facilitate the exact regulation of characteristics such as thermal properties and mechanical strength.

#### 3.1 Carbon-based fillers utilized for polymer composites containing ionic liquids

The incorporation of carbon-based fillers into polymer composites containing ionic liquids is a significant aspect



**Figure 4:** Chemical structures of (a) MWCNTs and (b) GO.

of enhancing their properties and functionalities. Table 4 shows examples of carbon-based fillers utilized for polymer composites containing ionic liquids. It can be noted that multiwalled carbon nanotubes (MWCNTs), graphene (Gra), expandable graphite (EG), and graphene oxide (GO) are usually utilized as carbon-based fillers in polymer composites containing ionic liquids. Figure 4 shows the chemical structures of MWCNTs and GO. MWCNTs have remarkable mechanical strength and electrical conductivity and serve as effective reinforcements (16), imparting mechanical integrity and facilitating electrical pathways within the composite. Gra is a two-dimensional carbon allotrope that contributes to the polymer composites' exceptional thermal, electrical, and mechanical performance due to its high surface area and intrinsic strength (25). EG acts as a flame retardant, enhancing the fire-resistant properties of the polymer composite (28) and making it valuable in applications where fire safety is paramount. GO has an oxygen-functionalized group that offers numerous opportunities for achieving both covalent and non-covalent adsorption of diverse functional molecules (52), improving the compatibility and overall

**Table 4:** Examples of carbon-based fillers utilized for polymer composites containing ionic liquids

Carbon-based filler	Abbreviation	References
Activated carbon	AC	(40)
Carbon fiber	CF	(51)
Carboxylated multiwalled carbon nanotubes	MWCNT-COOH	(41,57)
Expandable graphite	EG	(15,28,49,52,54)
Graphene	Gra	(17,18,25,33,53,59)
Graphene oxide	GO	(27,44,46,52)
Multiwalled carbon nanotubes	MWCNTs	(1,4,6,7,13,14,16,20,22,31,34,36–39,42,43,51,58,60–62)
Reduced graphene oxide	rGO	(31,36)
Single-walled carbon nanotubes	SWCNTs	(48,50)

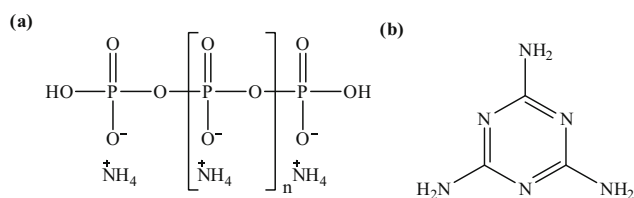
performance of the polymer composites. The collaboration between carbon-based fillers and ionic liquids presents a versatile strategy for customizing the properties of the composite, such as electrical conductivity, mechanical strength, and flame retardancy. This deliberate integration facilitates the creation of advanced materials suitable for various applications, from conductive components in electronics to flame-resistant structural elements. In conclusion, the intentional integration of carbon-based fillers, including MWCNTs, Gra, EG, and GO, with ionic liquids in polymer composites offers a versatile strategy for customizing properties, thus enabling the creation of advanced materials suitable for a wide range of applications, from electronics to structural elements requiring enhanced fire resistance.

### 3.2 Other fillers utilized for polymer composites containing ionic liquids

The exploration of various filler types for enhancing polymer composites containing ionic liquids extends beyond carbon-based options. Table 5 shows examples of other fillers utilized for polymer composites containing ionic liquids. It can be observed that inorganic-based, metal-based, and organic-based fillers are also utilized for polymer composites containing ionic liquids. Among inorganic-based fillers, APP, boron nitride nanosheets, silica, and sodium montmorillonite play pivotal roles, contributing to flame retardancy (56), enhanced thermal conductivity (12), improved mechanical strength (15), and barrier properties (8), broadening the

**Table 5:** Examples of other fillers utilized for polymer composites containing ionic liquids

Filler	Abbreviation	References
<b>Inorganic-based fillers</b>		
Aluminum hypophosphite	AHP	(45)
Ammonium polyphosphate	APP	(10,47,52,56)
Boron nitride nanosheets	BNNs	(12,19)
Glass microballoons	GM	(50)
Imogolite nanotubes	INTs	(47,56)
Nanohydroxyapatite	nHA	(4)
Nanotalc	n-Talc	(30)
Silica	SiO <sub>2</sub>	(15,55)
Sodium montmorillonite	NaMMT	(8,29)
<b>Metal-based fillers</b>		
Metal-organic frameworks	MOFs	(21)
Nickel ferrite	NiFe <sub>2</sub> O <sub>4</sub>	(32)
Tungsten	W	(35)
<b>Organic-based fillers</b>		
Melamine	MEL	(55)
Wood flour	WF	(28)



**Figure 5:** Chemical structures of (a) APP and (b) MEL.

potential applications of the composites in fire-resistant materials and structural components. Metal-based fillers, including metal-organic frameworks, nickel ferrite, and tungsten, bring distinctive functionalities such as fire retardancy (21), magnetic properties (32), and thermal stability (35), extending the utility of the composites in areas like fire safety and nanotechnology. Organic-based fillers, for example, melamine (MEL) and wood flour, introduce fire resistance (55) and biodegradability (28,63), reducing the heat release rate of the composite and tackling issues related to sustainability. Figure 5 shows the chemical structures of APP and MEL. The judicious selection and incorporation of these varied fillers into the polymer matrix, combined with the presence of ionic liquids, enables fine-tuning over a spectrum of properties such as flame resistance, thermal conductivity, and mechanical performance. This nuanced selection of fillers allows for customized composites that are apt for specific applications ranging from fire-resistant construction materials to eco-friendly packaging solutions. In conclusion, the strategic incorporation of diverse filler types, including inorganic-based, metal-based, and organic-based options, into polymer composites containing ionic liquids enables fine-tuning over a spectrum of properties, thus facilitating the creation of customized materials suitable for particular uses, spanning from flame-retardant building materials to environmentally conscious packaging options.

## 4 Ionic liquids employed in studies related to the thermal properties of polymer composites

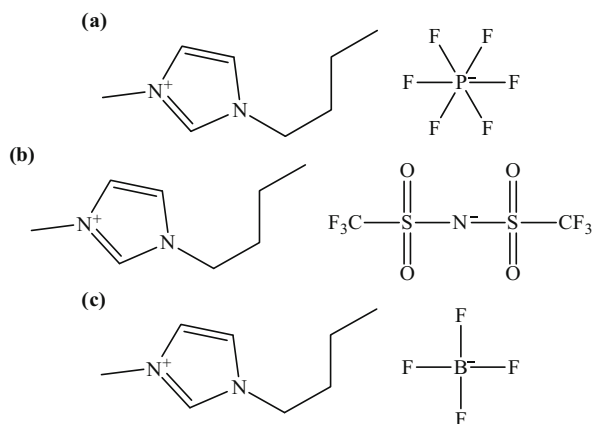
The discovery of ionic liquids in studies focusing on the thermal properties of polymer composites is outlined. Table 6 shows examples of ionic liquids employed in studies related to the thermal properties of polymer composites. It can be seen that imidazolium-based ionic liquids are employed more frequently than phosphonium-based ionic liquids and other types of ionic liquids. Imidazolium-based ionic liquids have garnered attention due to their

**Table 6:** Examples of ionic liquids employed in studies related to the thermal properties of polymer composites

Ionic liquid	Abbreviation	References
<b>Imidazolium-based</b>		
1-(2-Aminoethyl)-3-methylimidazolium bromide	[NC <sub>2</sub> mim][Br]	(41,44)
1-Butyl-3-methylimidazolium bromide	[C <sub>4</sub> mim][Br]	(32)
1-Butyl-3-methylimidazolium chloride	[C <sub>4</sub> mim][Cl]	(51)
1-Butyl-3-methylimidazolium hexafluorophosphate	[C <sub>4</sub> mim][PF <sub>6</sub> ]	(12,14,19,35,37,43,46,47,49,52,56)
1-Butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide	[C <sub>4</sub> mim][NTf <sub>2</sub> ]	(1,13,22,35,36,58,60,62)
1-Butyl-3-methylimidazolium hydrogen sulfate	[C <sub>4</sub> mim][HSO <sub>4</sub> ]	(4)
1-Butyl-3-methylimidazolium hypophosphite	[C <sub>4</sub> mim][H <sub>2</sub> PO <sub>2</sub> ]	(28)
1-Butyl-3-methylimidazolium phosphate	[C <sub>4</sub> mim][PO <sub>4</sub> ]	(54)
1-Butyl-3-methylimidazolium phosphomolybdate	[C <sub>4</sub> mim][PMo]	(40)
1-Butyl-3-methylimidazolium tetrafluoroborate	[C <sub>4</sub> mim][BF <sub>4</sub> ]	(31,34,35,53)
1-Carboxyethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide	[Cemim][NTf <sub>2</sub> ]	(57)
1-Decyl-3-methylimidazolium chloride	[C <sub>10</sub> mim][Cl]	(6)
3-(3-((Diphenylphosphoryl)amino)propyl)-1-methylimidazolium phosphomolybdate	[DPPNC <sub>3</sub> mim][PMo]	(21)
1-((Ethoxycarbonyl)methyl)-3-methylimidazolium bromide	[COOCmim][Br]	(25)
1-Ethyl-3-methylimidazolium acetate	[C <sub>2</sub> mim][Ac]	(4)
1-Ethyl-3-methylimidazolium chloride	[C <sub>2</sub> mim][Cl]	(55)
1-Ethyl-3-methylimidazolium hexafluorophosphate	[C <sub>2</sub> mim][PF <sub>6</sub> ]	(45)
1-Ethyl-3-methylimidazolium tetrafluoroborate	[C <sub>2</sub> mim][BF <sub>4</sub> ]	(15,16,50)
1-Hexadecyl-3-methylimidazolium bromide	[C <sub>16</sub> mim][Br]	(38,39,42)
1-Hexadecyl-3-methylimidazolium chloride	[C <sub>16</sub> mim][Cl]	(8)
1-Hexadecyl-3-methylimidazolium phosphomolybdate	[C <sub>16</sub> mim][PMo]	(40)
1-Hexyl-3-methylimidazolium hexafluorophosphate	[C <sub>6</sub> mim][PF <sub>6</sub> ]	(37)
1-Hydroxyethyl-3-methylimidazolium tetrafluoroborate	[HOC <sub>2</sub> mim][BF <sub>4</sub> ]	(59)
1-Methyl-3-((6-oxido-6 <i>H</i> -dibenzo[ <i>c,e</i> ][1,2]oxaphosphinin-6-yl)methyl)-3-imidazolium ethanesulfonate	[CODomim][EtSO <sub>3</sub> ]	(17)
1-Methyl-3-(3-((1-oxido-2,6,7-trioxa-1-phosphabicyclo[2.2.2]octan-4-yl)methoxy)-3-oxopropyl)-3-imidazolium hexafluorophosphate	[COTPOMopim][PF <sub>6</sub> ]	(18)
<i>N</i> -Octadecyl- <i>N</i> -octadecylimidazolium iodide	[C <sub>18</sub> oim][I]	(29)
1-Octyl-3-methylimidazolium tetrafluoroborate	[C <sub>8</sub> mim][BF <sub>4</sub> ]	(48)
1-(3-Perfluorooctylpropyl)-3-methylimidazolium bis(perfluoroethylsulfonyl)amide	[F <sub>8</sub> C <sub>3</sub> mim][NPF <sub>2</sub> ]	(20)
1,6-Bis(3-(vinylbenzyl)imidazolium-1-yl)hexane chloride	[Vinbnim][Cl]	(27)
1-Vinyl-3-ethylimidazolium bromide	[C <sub>2</sub> eim][Br]	(33)
1-Vinyl-3-ethylimidazolium tetrafluoroborate	[C <sub>2</sub> eim][BF <sub>4</sub> ]	(7)
<b>Phosphonium-based</b>		
Tetrabutylphosphonium tetrafluoroborate	[P <sub>4,4,4,4</sub> ][BF <sub>4</sub> ]	(10)
Trihexyl(tetradecyl)phosphonium bis(trifluoromethylsulfonyl)imide	[P <sub>6,6,6,14</sub> ][NTf <sub>2</sub> ]	(30)
Trihexyl(tetradecyl)phosphonium bis(2,4,4-trimethylpentyl)phosphinate	[P <sub>6,6,6,14</sub> ][TMPP]	(30)
Triphenyl(octadecyl)phosphonium iodide	[P <sub>ph,ph,ph,18</sub> ][I]	(29)
<b>Others</b>		
1-Butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide	[C <sub>4</sub> mpy][NTf <sub>2</sub> ]	(35)
Tributylmethylammonium bis(trifluoromethylsulfonyl)imide	[N <sub>4,4,4,1</sub> ][NTf <sub>2</sub> ]	(16)

diverse and tunable physicochemical properties, enabling meticulous adjustments to the thermal behavior of polymer composites. This adaptability is evidenced by their impact on critical parameters, including glass transition temperature (34), melting temperature (31), degradation temperature (19), and thermal conductivity (13). These parameters are integral to comprehending and optimizing the thermal performance of polymer composites, solidifying the role of imidazolium-based ionic liquids in this study. Many types of imidazolium-based ionic liquids have been identified, each

attracting interest for their ability to precisely tailor the thermal behavior of polymer composites. Their versatility extends to influencing key parameters, providing a comprehensive approach to customizing thermal properties. Notable examples include 1-butyl-3-methylimidazolium hexafluorophosphate ([C<sub>4</sub>mim][PF<sub>6</sub>]), 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([C<sub>4</sub>mim][NTf<sub>2</sub>]), and 1-butyl-3-methylimidazolium tetrafluoroborate ([C<sub>4</sub>mim][BF<sub>4</sub>]), which have found widespread application in polymer composites.



**Figure 6:** Chemical structures of (a)  $[\text{C}_4\text{mim}][\text{PF}_6]$ , (b)  $[\text{C}_4\text{mim}][\text{NTf}_2]$ , and (c)  $[\text{C}_4\text{mim}][\text{BF}_4]$ .

Their popularity can be attributed to factors such as reasonable cost, obtainability, and efficacy in enhancing composite properties. Figure 6 shows the chemical structures of  $[\text{C}_4\text{mim}][\text{PF}_6]$ ,  $[\text{C}_4\text{mim}][\text{NTf}_2]$ , and  $[\text{C}_4\text{mim}][\text{BF}_4]$ . Additionally, the employment of a few phosphonium-based ionic liquids introduces an extra layer to the modulation of thermal characteristics in polymer composites. Further diversifying the study, researchers have examined other ionic liquid types, including pyrrolidinium-based (35) and ammonium-based (16) ionic liquids, extending the scope and acknowledging the broad possibilities for tailoring thermal properties. This systematic observation of various ionic liquid variants underscores the ongoing potential for researchers to delve into additional variations. By comprehensively understanding the diverse landscape of ionic liquids, researchers are equipped to explore new probabilities, contributing to the continuous advancement of materials tailored for specific applications within the realm of polymer composites. In conclusion, the systematic exploration of imidazolium-based ionic liquids, alongside other variants such as phosphonium-based, pyrrolidinium-based, and ammonium-based ionic liquids, underscores their pivotal role in finely tuning the thermal properties of polymer composites, offering researchers a diverse landscape to explore and continually advance materials customized for particular applications in this field.

## 5 Thermal properties of polymer composites containing ionic liquids

Investigating the thermal properties of polymer composites containing ionic liquids stands as a frontier in materials

science, where the synergy between various ionic liquids and fillers imparts a range of tunable thermal characteristics. In thermoplastic composites, the matrix's reversible nature allows for facile processing and reshaping, and the integration of ionic liquids becomes vital in precisely adjusting glass transition temperature, melting temperature, and degradation temperature. For thermosetting composites, characterized by irreversible curing reactions, strategic integration of ionic liquids enhances properties, influencing key parameters like glass transition temperature, degradation temperature, and thermal conductivity. Elastomer composites, prized for their flexibility and resilience, undergo significant improvements with the integration of ionic liquids, presenting unique opportunities to modulate critical thermal parameters such as glass transition temperature, melting temperature, degradation temperature, and thermal conductivity, particularly in the context of stretchable materials. This exploration into tailored thermal characteristics not only advances the understanding of these composite materials but also opens new vistas for the development of applications in diverse fields, spanning from electronics to aerospace.

### 5.1 Thermal properties of thermoplastic composites containing ionic liquids

The investigation of thermal properties is crucial in evaluating the performance of thermoplastic composites. Table 7 shows the thermal properties of thermoplastic composites containing ionic liquids. The melting and degradation temperatures of the PA6/rGO/MWCNTs composites containing  $[\text{C}_4\text{mim}][\text{BF}_4]$  were investigated by Zhao *et al.* (31). They revealed that the melting temperature of the composites was impacted by the integration of  $[\text{C}_4\text{mim}][\text{BF}_4]$ . However, there is an improvement in the degradation temperature of the composite at 0.3 wt% of rGO/MWCNTs- $[\text{C}_4\text{mim}][\text{BF}_4]$  (453.2°C) as compared to the neat PA6 (440.5°C). The enhanced thermal stability of the composite can be ascribed to the thermal barrier effect resulting from the network structure established by rGO/MWCNTs- $[\text{C}_4\text{mim}][\text{BF}_4]$  within the PA6 matrix (31). Potential applications for these composites include multi-functional and high-performance composite fibers and textiles, where the improved thermal stability provided by the integrated  $[\text{C}_4\text{mim}][\text{BF}_4]$  can enhance the overall performance and durability of the composite materials.

The melting and degradation temperatures of the PEEK/MWCNTs/nHA composites containing  $[\text{C}_4\text{mim}][\text{HSO}_4]$  were investigated by Ahmad *et al.* (4). They discovered



**Table 7:** Thermal properties of thermoplastic composites containing ionic liquids

Thermoplastic composite	Ionic liquid	Cont. (%)	Thermal properties			Ref.
			$T_g$ (°C)	$T_m$ (°C)	$T_d$ (°C)	
PA6/rGO/MWCNTs	[C <sub>4</sub> mim][BF <sub>4</sub> ]	0.3	—	221.8↓	453.2↑	(31)
PEEK/MWCNTs/nHA	[C <sub>4</sub> mim][HSO <sub>4</sub> ]	1.0	—	353.0↑	581.0↑	(4)
PEI/MWCNTs	[C <sub>4</sub> mim][BF <sub>4</sub> ]	4.0	215.1↓	—	529.8↓	(34)
PLA/APP	[P <sub>4,4,4,4</sub> ][BF <sub>4</sub> ]	1.5	60.0↑	168.0↑	363.0↓	(10)
PLA/Gra	[COTPOMopim][PF <sub>6</sub> ]	4.0	62.2↑	168.0↓	364.5↑	(18)
PMMA/GO	[Vinbnim][Cl]	2.08	131.9↑	—	~300↑	(27)
PMMA/MWCNTs	[C <sub>4</sub> mim][PF <sub>6</sub> ]	10	75.4↓	—	U↑	(14)
PMMA/rGO/MWCNTs	[C <sub>4</sub> mim][NTf <sub>2</sub> ]	3.0	—	U↑	U↑	(36)
PP/PA6/n-Talc	[P <sub>6,6,6,14</sub> ][TMPP]	10	—	165.2↑	373.1↑	(30)
PVDF/MWCNT-COOH	[NC <sub>2</sub> mim][Br]	1.0	-33.8↑	175.0↑	—	(41)

$T_g$  = glass transition temperature,  $T_m$  = melting temperature,  $T_d$  = degradation temperature, and U = unstated.

that there is an increment in the melting temperature of the composite at 1.0 wt% of [C<sub>4</sub>mim][HSO<sub>4</sub>] (353.0°C) in comparison with the composite without [C<sub>4</sub>mim][HSO<sub>4</sub>] (347.0°C). The increased thermal resistance of the composite can be attributed to the uniformly dispersed MWCNTs served as efficient nucleating agents, facilitating rapid PEEK crystallization (4). The degradation temperature of the composite (581.0°C) was also higher than that of the composite without the ionic liquid (570.0°C). This enhancement is a result of the prevention of agglomeration and the  $\pi$ - $\pi$  stacking interactions between MWCNTs modified with [C<sub>4</sub>mim][HSO<sub>4</sub>] and PEEK (4). Potential applications for these composites include promising biomedical and structural applications, where the enhanced melting and degradation temperatures alongside improved dispersion facilitated by [C<sub>4</sub>mim][HSO<sub>4</sub>] can provide superior thermal properties for demanding applications.

The glass transition and degradation temperatures of the PEI/MWCNTs composites containing [C<sub>4</sub>mim][BF<sub>4</sub>] were investigated by Ke et al. (34). They revealed that the glass transition temperature of the composite was decreased as [C<sub>4</sub>mim][BF<sub>4</sub>] content increased by 4.0 wt%. This suggests that [C<sub>4</sub>mim][BF<sub>4</sub>] can serve as a plasticizer in the PEI matrix. Moreover, there is a deterioration in the degradation temperature of the composite. The inferior thermal stability of the composite can be ascribed to the fact that [C<sub>4</sub>mim][BF<sub>4</sub>] exhibits somewhat lower thermal stability in comparison to PEI (34). Potential applications for these composites include composite fibers and lightweight structural components, where the reduced glass transition temperature provided by [C<sub>4</sub>mim][BF<sub>4</sub>] may be advantageous for processing, and the composite material's overall properties meet the application requirements.

The glass transition, melting, and degradation temperatures of the PLA/APP composites containing [P<sub>4,4,4,4</sub>][BF<sub>4</sub>] were investigated by Jia et al. (10). They discovered that the glass transition and melting temperatures of the composites are the same as the neat PLA, which are observed at temperatures of 60.0°C and 168.0°C. Nonetheless, there is a slight decrease in the degradation temperature of the composite as [P<sub>4,4,4,4</sub>][BF<sub>4</sub>] content increased by 1.5 wt%. The lower thermal stability of the composite is due to the possibility of an interaction between PLA and [P<sub>4,4,4,4</sub>][BF<sub>4</sub>] during the thermal decomposition process (10). Potential applications for these composites include environmentally friendly packaging materials and biodegradable coatings, where the retention of PLA's glass transition and melting temperatures from the integrated [P<sub>4,4,4,4</sub>][BF<sub>4</sub>] can offer versatile solutions for various industries.

The glass transition, melting, and degradation temperatures of the PLA/Gra composites containing [COTPOMopim][PF<sub>6</sub>] were investigated by Gui et al. (18). They revealed that there is a slight improvement in the glass transition temperature of the composite at 4.0 wt% of Gra-[COTPOMopim][PF<sub>6</sub>] (62.2°C) as compared to the neat PLA (60.4°C). There was a slight reduction in the melting temperature of the composite, which was attributed to their crystals' being less organized (18). Nevertheless, the degradation temperature of the composite (364.5°C) was higher than that of the neat PLA (351.1°C). This enhancement is due to the effective physical barrier provided by the Gra-[COTPOMopim][PF<sub>6</sub>] layers and the robust interfacial interactions between Gra-[COTPOMopim][PF<sub>6</sub>] and PLA (18). Potential applications for these composites include biodegradable packaging materials and sustainable construction materials, where the combination of improved thermal stability and potentially

enhanced barrier properties facilitated by Gra-[COTPO-Mopim][PF<sub>6</sub>] layers can offer multi-functional solutions for various industries seeking eco-friendly alternatives.

The glass transition and degradation temperatures of the PMMA/GO composites containing [Vinbnim][Cl] were investigated by Yang *et al.* (27). They discovered that there is an increase in the glass transition temperature of the composite at 2.08 vol.% of GO-[Vinbnim][Cl] (131.9°C) as compared to the neat PMMA (112.7°C). This improvement is because the synergistic effects create substantial geometrical limitations on the mobility of the PMMA chains (27). The degradation temperature of the composite (~300°C) was also higher than that of the neat PMMA (~190°C). This enhancement is owing to the inherent high thermal stability of GO-[Vinbnim][Cl], which could serve as an effective barrier, decreasing the permeability of volatile gas during thermal decomposition (27). Potential applications for these composites include durable coatings and flame-retardant materials, where the combination of increased glass transition temperature and enhanced thermal stability provided by GO-[Vinbnim][Cl] can offer improved thermal properties for demanding applications.

The glass transition and degradation temperatures of the PMMA/MWCNTs composites containing [C<sub>4</sub>mim][PF<sub>6</sub>] were investigated by Zhao *et al.* (14). They revealed that the glass transition temperature of the composite was reduced as [C<sub>4</sub>mim][PF<sub>6</sub>] content raised by 10 wt%. The reduction in the glass transition temperature in the composite implies the plasticizing effect of the employed [C<sub>4</sub>mim][PF<sub>6</sub>]. However, there is an increase in the degradation temperature of the composite (>20°C) compared to the neat PMMA. The heightened thermal stability is a result of the strong compatibility between [C<sub>4</sub>mim][PF<sub>6</sub>] and the PMMA matrix, along with the improved dispersion of MWNTs and the enhanced interface facilitated by [C<sub>4</sub>mim][PF<sub>6</sub>] (14). Potential applications for these composites include flexible electronics and optoelectronic devices, where the combination of improved thermal stability and compatibility provided by [C<sub>4</sub>mim][PF<sub>6</sub>] can enable the development of high-performance and durable components for various technological applications.

The melting and degradation temperatures of the PMMA/rGO/MWCNTs composites containing [C<sub>4</sub>mim][NTf<sub>2</sub>] were investigated by Sa *et al.* (36). They discovered that there is an enhancement in the melting temperature of the composite as MWCNTs-[C<sub>4</sub>mim][NTf<sub>2</sub>] content increased by 3.0 wt%. This enhancement is due to the PMMA chains being confined within a restricted space to enable movement (36). In addition, the degradation temperature of the composite was higher than those of the neat PMMA and the composite without MWCNTs-[C<sub>4</sub>mim][NTf<sub>2</sub>]. The improved thermal stability of the composite could result from the

robust interaction provided by MWCNTs-[C<sub>4</sub>mim][NTf<sub>2</sub>] with the PMMA matrix (36). Potential applications for these composites include high-performance materials and electromagnetic interference shielding coatings, where the enhanced melting and degradation temperatures facilitated by MWCNTs-[C<sub>4</sub>mim][NTf<sub>2</sub>] can offer versatile solutions for various demanding applications requiring superior thermal and electrical performance.

The melting and degradation temperatures of the PP/PA6/n-Talc composites containing [P<sub>6,6,6,14</sub>][TMPP] were investigated by Yousfi *et al.* (30). They revealed that the melting temperatures of the composites (PP matrix) are almost the same as the PP/PA6 blend without n-Talc-[P<sub>6,6,6,14</sub>][TMPP]. However, there is an improvement in the degradation temperature of the composite as n-Talc-[P<sub>6,6,6,14</sub>][TMPP] content raised by 10 wt% (373.1°C) in comparison with the PP/PA6 blend (291.7°C). The enhanced thermal stability of the composite may be attributed to the synergistic interaction between n-Talc and [P<sub>6,6,6,14</sub>][TMPP] (30). Potential applications for these composites include automotive parts and construction components, where the improved thermal stability provided by the synergistic interaction n-Talc-[P<sub>6,6,6,14</sub>][TMPP] can offer enhanced performance in high-temperature environments, contributing to the durability and longevity of the final products.

The glass transition and melting temperatures of the PVDF/MWCNT-COOH composites containing [NC<sub>2</sub>mim][Br] were investigated by Mandal and Nandi (41). They discovered that there is an increment in the glass transition temperature of the composite at 1.0 wt% of MWCNT-COOH-[NC<sub>2</sub>mim][Br] (-33.8°C) as compared to the neat PVDF (-42.5°C). The improved glass transition temperature of the composite can be linked to the heightened compactness of the PVDF amorphous region, a result of the robust surface force between the MWNT-COOH-[NC<sub>2</sub>mim][Br] (41). Additionally, the melting temperature of the composite (175.0°C) was higher than that of the neat PVDF (165.0°C). The elevated melting temperature of the composite could be ascribed to the creation of a greater quantity of β-phase crystals (41). Potential applications for these composites include sensors and actuators, where the enhanced glass transition and melting temperatures provided by MWCNT-COOH-[NC<sub>2</sub>mim][Br] can offer improved stability and performance in harsh environmental conditions.

## 5.2 Thermal properties of thermosetting composites containing ionic liquids

Understanding the thermal behavior of thermosetting composites is essential for assessing their applicability

in various industries. Table 8 shows the thermal properties of thermosetting composites containing ionic liquids. The degradation temperature and thermal conductivity of the EP/BNNs composites containing [C<sub>4</sub>mim][PF<sub>6</sub>] were investigated by Li et al. (19). They revealed that there is a deterioration in the degradation temperature of the composite at 12.1 vol.% of BNNs-[C<sub>4</sub>mim][PF<sub>6</sub>] as compared to the composite without [C<sub>4</sub>mim][PF<sub>6</sub>]. The lower thermal stability of the composite can be attributed to the initial degradation of [C<sub>4</sub>mim][PF<sub>6</sub>] (those that are not cross-linked within the EP networks) at lower temperatures (19). Nevertheless, the thermal conductivity of the composite (1.04 W·m<sup>-1</sup>·K<sup>-1</sup>) was higher than that of the composite without the ionic liquid (0.79 W·m<sup>-1</sup>·K<sup>-1</sup>). This improvement is due to the presence of [C<sub>4</sub>mim][PF<sub>6</sub>] immobilized on BNNs, which enhances conductivity (19). Potential applications for these composites include thermal interface materials and aerospace structural components, where the enhanced thermal conductivity provided by the immobilized [C<sub>4</sub>mim][PF<sub>6</sub>] can improve heat dissipation and thermal management, leading to more efficient and reliable operation in demanding thermal environments.

The glass transition and degradation temperatures of the EP/SWCNTs composites containing [C<sub>8</sub>mim][BF<sub>4</sub>] were investigated by Sanes et al. (48). They discovered that there is a slight increase in the glass transition temperature of the composite at 2.0 wt% of SWCNTs-[C<sub>8</sub>mim][BF<sub>4</sub>] (98.8°C) as compared to the composite without [C<sub>8</sub>mim][BF<sub>4</sub>] (95.9°C). The increased glass transition temperature of the composite might explain its enhanced thermal stability, as discussed below. The degradation temperature of the composite (388.6°C) was also higher than that of the neat EP (368.7°C) and the composite without the ionic liquid (366.6°C). This enhancement is due to the effect of the high thermal stability of [C<sub>8</sub>mim][BF<sub>4</sub>] (417.0°C) (48). Potential applications for these composites include tribological applications and high-performance materials, where the enhanced glass transition temperature and thermal stability provided by [C<sub>8</sub>mim][BF<sub>4</sub>] can offer improved thermal

properties, contributing to the durability of the final products in challenging environments.

The glass transition and degradation temperatures of the PI/Gra composites containing [C<sub>4</sub>mim][BF<sub>4</sub>] were investigated by Ruan et al. (53). They revealed that there is an increment in the glass transition temperature of the composite at 0.4 wt% of Gra-[C<sub>4</sub>mim][BF<sub>4</sub>] (265.2°C) as compared to the neat PI (251.2°C). The increased glass transition temperature of the composite can be ascribed to the even distribution of Gra-[C<sub>4</sub>mim][BF<sub>4</sub>] in the PI phase and its robust covalent adhesion to the PI matrix, which impedes the movement of the PI chains (53). Moreover, the degradation temperature of the composite (581.3°C) was higher than that of the neat PI (528.7°C). This heightening is owing to the interaction between [C<sub>4</sub>mim][BF<sub>4</sub>] and Gra via  $\pi$ - $\pi$ , cation- $\pi$ , and van der Waals interactions, ultimately increasing the interfacial compatibility and stability of Gra-[C<sub>4</sub>mim][BF<sub>4</sub>] with the matrix (53). Potential applications for these composites include high-temperature self-lubricating materials and automotive structural components, where the enhanced glass transition temperature and thermal stability provided by Gra-[C<sub>4</sub>mim][BF<sub>4</sub>] can offer superior thermal properties, ensuring reliability and performance in extreme conditions.

The degradation temperature and thermal conductivity of the RPU/EG/SiO<sub>2</sub> composites containing [C<sub>2</sub>mim][BF<sub>4</sub>] were investigated by Strąkowska et al. (15). They discovered that there is a deterioration in the degradation temperature of the composite at 0.33 wt% of [C<sub>2</sub>mim][BF<sub>4</sub>] as compared to the composite without [C<sub>2</sub>mim][BF<sub>4</sub>]. The reduced thermal stability of the composite suggests that the presence of the ionic liquid did not impact and, in fact, diminished the stability. Nonetheless, the thermal conductivity of the composite (25.30 mW·(m·K)<sup>-1</sup>) was higher than that of the composite without the ionic liquid (24.90 mW·(m·K)<sup>-1</sup>). This enhancement is likely due to the modifications in the composite structure, leading to alterations in conductivity (15). Potential applications for these composites include construction materials and heat

**Table 8:** Thermal properties of thermosetting composites containing ionic liquids

Thermosetting composite	Ionic liquid	Cont. (%)	Thermal properties			Ref.
			$T_g$ (°C)	$T_d$ (°C)	$k$ (W·m <sup>-1</sup> ·K <sup>-1</sup> )	
EP/BNNs	[C <sub>4</sub> mim][PF <sub>6</sub> ]	12.1	—	390.0↓	1.04↑	(19)
EP/SWCNTs	[C <sub>8</sub> mim][BF <sub>4</sub> ]	1.5	98.8↑	388.6↑	—	(48)
PI/Gra	[C <sub>4</sub> mim][BF <sub>4</sub> ]	0.4	265.2↑	581.3↑	—	(53)
RPU/EG/SiO <sub>2</sub>	[C <sub>2</sub> mim][BF <sub>4</sub> ]	0.33	—	591.0↓	25.30↑	(15)
RPU/MEL/SiO <sub>2</sub>	[C <sub>2</sub> mim][Cl]	0.3	169.0↑	571.0↑	U↑	(55)

$T_g$  = glass transition temperature,  $T_d$  = degradation temperature,  $k$  = thermal conductivity, and U = unstated.

exchangers, where the enhanced thermal conductivity provided by [C<sub>2</sub>mim][BF<sub>4</sub>] can improve heat transfer efficiency, contributing to the overall performance and energy efficiency of the applications.

The glass transition and degradation temperatures, as well as the thermal conductivity of the RPU/MEL/SiO<sub>2</sub> composites containing [C<sub>2</sub>mim][Cl], were investigated by Członka *et al.* (55). They revealed that there is an improvement in the glass transition temperature of the composite at 0.3 wt% of [C<sub>2</sub>mim][Cl] (169.0°C) as compared to the neat RPU (142.0°C). This improvement is attributable to the heightened cross-link density and rigidity of the RPU structure resulting from the inclusion of MEL/SiO<sub>2</sub>-[C<sub>2</sub>mim][Cl] (55). The degradation temperature of the composite (571.0°C) was also higher than that of the neat RPU (566.0°C). The elevated degradation temperature of the composite also implies that the inclusion of MEL/SiO<sub>2</sub>-[C<sub>2</sub>mim][Cl] improved its thermal stability. Furthermore, there was an increase in the thermal conductivity of the composite, which can be attributed to the higher content of open cells caused by a high amount of MEL/SiO<sub>2</sub>-[C<sub>2</sub>mim][Cl] in the composite (55). Potential applications for these composites include thermal management solutions and heat-resistant coatings, where the improved glass transition temperature, thermal stability, and thermal conductivity provided by MEL/SiO<sub>2</sub>-[C<sub>2</sub>mim][Cl] can enhance the overall efficiency and durability of the materials in various demanding environments.

### 5.3 Thermal properties of elastomer composites containing ionic liquids

Examining the thermal characteristics of elastomer composites provides valuable insights into their potential applications. Table 9 shows the thermal properties of elastomer composites containing ionic liquids. The glass transition and degradation temperatures of the CR/MWCNTs composites containing [C<sub>4</sub>mim][NTf<sub>2</sub>] were investigated by

Subramaniam *et al.* (58). They discovered that the glass transition temperature of the composite at 5 phr of [C<sub>4</sub>mim][NTf<sub>2</sub>] is almost similar to the composite without [C<sub>4</sub>mim][NTf<sub>2</sub>]. Besides that, there is an increase in the degradation temperature of the [C<sub>4</sub>mim][NTf<sub>2</sub>]-modified MWCNTs (467.0°C) as compared to the control [C<sub>4</sub>mim][NTf<sub>2</sub>] (444.0°C). This increase is due to the binding of [C<sub>4</sub>mim][NTf<sub>2</sub>] to MWCNTs, facilitated by cation- $\pi/\pi$ - $\pi$  interactions or basic van der Waals forces, which render [C<sub>4</sub>mim][NTf<sub>2</sub>] more thermally stable (58). Potential applications for these composites include electrical conductive materials and corrosion-resistant components, where the improved thermal stability provided by [C<sub>4</sub>mim][NTf<sub>2</sub>]-modified MWCNTs can enhance the overall performance and durability of the composite materials in harsh conditions.

The glass transition, melting, and degradation temperatures of the EVM/MWCNTs composites containing [C<sub>2</sub>mim][BF<sub>4</sub>] were investigated by Cao *et al.* (16). They revealed that the glass transition and melting temperatures of the composite at 10 phr of [C<sub>2</sub>mim][BF<sub>4</sub>] are about the same as the neat EVM, which are observed at temperatures of -27.3°C and 42.9°C. In addition, there is no significant distinction perceived between the composite with MWCNTs-[C<sub>2</sub>mim][BF<sub>4</sub>] and the composite with pristine MWCNTs concerning degradation temperature. This phenomenon is ascribed to the unique interaction between MWCNTs, [C<sub>2</sub>mim][BF<sub>4</sub>], and EVM (16). Potential applications for these composites include flexible conductive materials and high-performance materials, where the particular interaction between MWCNTs, [C<sub>2</sub>mim][BF<sub>4</sub>], and EVM can provide tailored thermal properties suitable for diverse and specific industrial applications.

The glass transition temperature and thermal conductivity of the HXNBR/HNBR/MWCNTs composites containing [C<sub>4</sub>mim][NTf<sub>2</sub>] were investigated by Yin *et al.* (13). They discovered that there is a slight reduction in the glass transition temperature of the composite at 15 phr of [C<sub>4</sub>mim][NTf<sub>2</sub>] as compared to the HXNBR/HNBR blend. The reduced glass transition temperature of the composite is associated with

**Table 9:** Thermal properties of elastomer composites containing ionic liquids

Elastomer composite	Ionic liquid	Cont. (phr)	Thermal properties				Ref.
			$T_g$ (°C)	$T_m$ (°C)	$T_d$ (°C)	$k$ (W·m <sup>-1</sup> ·K <sup>-1</sup> )	
CR/MWCNTs	[C <sub>4</sub> mim][NTf <sub>2</sub> ]	5	-38.0†	—	467.0†	—	(58)
EVM/MWCNTs	[C <sub>2</sub> mim][BF <sub>4</sub> ]	10	-27.3†	42.9†	U†	—	(16)
HXNBR/HNBR/MWCNTs	[C <sub>4</sub> mim][NTf <sub>2</sub> ]	15	-28.9‡	—	—	0.29†	(13)
NR/MWCNTs	[C <sub>4</sub> mim][NTf <sub>2</sub> ]	5	-51.4†	—	385.3‡	—	(22)

$T_g$  = glass transition temperature,  $T_m$  = melting temperature,  $T_d$  = degradation temperature,  $k$  = thermal conductivity, and U = unstated.

the plasticizing effect of  $[C_4mim][NTf_2]$ , which can induce the softening of HXNBR/HNBR chains (13). Nevertheless, the thermal conductivity of the composite ( $0.29\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) was higher than that of the HXNBR/HNBR blend ( $0.23\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ). This heightening is owing to the decreased contact thermal resistance in the system, a result of the improved dispersibility of  $[C_4mim][NTf_2]$ -modified MWCNTs (13). Potential applications for these composites include automotive seals and gaskets, where the enhanced thermal conductivity provided by  $[C_4mim][NTf_2]$ -modified MWCNTs can contribute to better heat dissipation, ensuring optimal performance and durability of the components for high-temperature environments.

The glass transition and degradation temperatures of the NR/MWCNTs composites containing  $[C_4mim][NTf_2]$  were investigated by Krainoi et al. (22). They revealed that there is an improvement in the glass transition temperature of the composite at 5 phr of MWCNTs- $[C_4mim][NTf_2]$  ( $-51.4^\circ\text{C}$ ) as compared to the gum NR ( $-52.7^\circ\text{C}$ ). This improvement is attributed to the positive interactions between MWCNTs and NR assisted by  $[C_4mim][NTf_2]$ , promoting the dispersion and the formation of three-dimensional filler networks. Consequently, the established filler networks constrained the molecular mobility or flexibility of NR (22). However, there was a deterioration in the degradation temperature of the composite. The inferior thermal stability of the composite can be linked to the high thermal conductivity of MWCNTs and the low molecular weight of  $[C_4mim][NTf_2]$  (22). Potential applications for these composites include electroactive elastomers and stretchable thermal conductors, where the improved glass transition temperature and enhanced dispersion of MWCNTs facilitated by  $[C_4mim][NTf_2]$  can offer superior thermal properties and stability, ensuring reliable performance in demanding industrial applications.

## 6 Conclusions

In this review, the examples of polymer matrices and fillers used for polymer composites containing ionic liquids, as well as examples of ionic liquids employed in studies related to the thermal properties of these composites, are briefly covered. The thermal properties, such as glass transition temperature, melting temperature, degradation temperature, and thermal conductivity of polymer composites containing ionic liquids, are also revisited in this mini-review. Imidazolium-based ionic liquids were found to be frequently employed in studies related to the thermal

properties of polymer composites. In most investigations, thermoplastic composites containing ionic liquids (particularly  $[C_4mim][HSO_4]$ ,  $[COTPOMopim][PF_6]$ ,  $[Vinbnim][Cl]$ ,  $[C_4mim][NTf_2]$ , and  $[NC_2mim][Br]$ ) exhibited high glass transition, melting, and degradation temperatures. In addition, thermosetting composites containing ionic liquids (especially  $[C_8mim][BF_4]$ ,  $[C_4mim][BF_4]$ , and  $[C_2mim][Cl]$ ) demonstrated elevated glass transition and degradation temperatures, as well as enhanced thermal conductivity. Similarly, elastomer composites containing ionic liquid (specifically  $[C_4mim][NTf_2]$ ) showcased elevated glass transition and degradation temperatures along with improved thermal conductivity. The improvement in the glass transition temperature is often attributed to synergistic interactions between the filler and ionic liquid, coupled with the enhanced dispersion of filler–ionic liquid in the polymer matrix, hindering the mobility of polymer chains. The increase in the degradation temperature is generally ascribed to the effective thermal barrier provided by the filler–ionic liquid and the robust interfacial interactions between the filler–ionic liquid and the polymer matrix, thereby increasing the thermal stability of polymer composites. The enhancement in thermal conductivity typically results from the modification of the structure of polymer composites, reducing their contact thermal resistance.

Among the ionic liquids investigated for their efficacy in enhancing the thermal properties of polymer composites, imidazolium-based ionic liquids with tetrafluoroborate, bis(trifluoromethylsulfonyl)imide, hexafluorophosphate, halides, and hydrogen sulfate anions emerge as a favorable choice considering aspects like environmental friendliness, cost-effectiveness, and efficiency in interacting with polymer composites. Their use has shown notable improvements in glass transition and degradation temperatures, as well as enhanced thermal conductivity in various polymer matrices. With their relatively accessible, more straightforward synthesis pathway, and robust performance in improving composite characteristics, imidazolium-based ionic liquids with the anions mentioned above present themselves as promising options for applications requiring enhanced thermal stability and conductivity without compromising on sustainability or economic feasibility.

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