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A review on recent advances in epdm/nbr-based rubber blends: structure, properties, applications and sustainability

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Ethylene Propylene Diene Monomer (EPDM) and Nitrile Butadiene Rubber (NBR) are two industrially significant elastomers with complementary properties – EPDM provides excellent resistance to ozone, weathering, and thermal aging, while NBR exhibits superior oil and hydrocarbon resistance. However, their inherent immiscibility due to polarity differences limits direct blending, leading to phase separation and poor interfacial adhesion. This review critically examines recent strategies to enhance the compatibility and performance of EPDM/NBR blends, including chemical compatibilizers such as maleic anhydride grafted EPDM (MAH-g-EPDM), epoxidized EPDM (Ep-EPDM), aminated Ep-EPDM (Am-Ep-EPDM), and bromobutyl rubber (BIIR). Nanofiller incorporation, particularly organo-modified nanoclays, improves morphology control, crosslinking density, thermal stability, and mechanical reinforcement. Fiber reinforcement, especially with short aramid fibers at optimized orientation angles, enhances ablation resistance and char layer integrity for high-temperature applications. The effects of different curing systems (sulfur vs. peroxide) on vulcanization kinetics, network structure, and long-term aging are also discussed. The review summarizes findings from multiple studies to provide a comprehensive understanding of the structure–property relationships, thermal and mechanical performance, and application-specific suitability of EPDM/NBR composites. These multifunctional blends demonstrate significant potential for automotive, aerospace, and industrial applications where a combination of oil resistance, thermal stability and durability is required. Future research directions include eco-friendly compatibilization, advanced nanofillers, digital process control, and sustainable recycling strategies to further enhance performance and eco-compatibility.

Keywords: EPDM, NBR, rubber blends, polymer composites, thermal stability, mechanical properties, thermal stability

Огляд останніх досягнень у розробці гумових сумішей на основі epdm/nbr: структура, властивості, застосування та сталий розвиток. *Fariz Amirli, Rana Khankishiyeva, Aynur Mammadova, Maxsud Jumaniyazo*

Етиленпропілендієновий мономер (EPDM) та нітрилбутадієновий каучук (NBR) – це два промислово значущі еластомери з взаємодоповнюючими властивостями: EPDM забезпечує

чудову стійкість до озону, атмосферних впливів та термічного старіння, тоді як NBR демонструє чудову стійкість до олії та вуглеводнів. Однак їхня властива незмішуваність через різницю в полярності обмежує пряме змішування, що призводить до розділення фаз та поганої міжфазної адгезії. У цьому огляді критично розглядаються новітні стратегії для підвищення сумісності та експлуатаційних характеристик сумішей EPDM/NBR, включаючи хімічні компатибілізатори, такі як EPDM, щеплений малеїновим ангідридом (MAH-g-EPDM), епоксидований EPDM (Ep-EPDM), амінований Ep-EPDM (Am-Ep-EPDM) та бромбутиловий каучук (BIIR). Включення нанонаповнювачів, зокрема органомодифікованих наноглин, покращує контроль морфології, щільність зшивання, термічну стабільність та механічне армування. Армування волокнами, особливо короткими аramідними волокнами з оптимізованими кутами орієнтації, підвищує стійкість до абляції та цілісність шару обвуглювання для застосування при високих температурах. Також обговорюється вплив різних систем вулканізації (сірка проти пероксиду) на кінетику вулканізації, структуру мережі та тривале старіння. В огляді синтезовано результати численних досліджень, щоб забезпечити комплексне уявлення про взаємозв'язки між структурою та властивостями, теплові та механічні характеристики, а також придатність композитів EPDM/NBR для конкретних застосувань. Ці багатофункціональні суміші демонструють значний потенціал для автомобільної, аерокосмічної та промислової галузей, що вимагають комбінованої стійкості до олії, термостабільності та довговічності. Майбутні напрямки досліджень включають екологічно чисту сумісність, передові нанонаповнювачі, цифрове управління процесами та стратегії сталого перероблення для подальшого підвищення продуктивності та екологічної сумісності.

1. Introduction

Ethylene propylene diene monomer (EPDM) and nitrile butadiene rubber (NBR) are two commercially important synthetic elastomers that are widely used in sealing, automotive, construction, oil-resistant, and high-temperature engineering applications. Their importance arises from the fact that they possess different but complementary performance profiles. EPDM is a saturated, non-polar elastomer with excellent resistance to ozone, ultraviolet radiation, weathering, oxidation, and thermal aging. These characteristics make it suitable for outdoor seals, automotive weather strips, roofing membranes, cable insulation, thermal barriers, and other components exposed to long-term environmental stress. However, EPDM shows limited resistance to petroleum oils, fuels, and hydrocarbon-based fluids, which restricts its application in oil-contacting environments [1–3].

NBR, on the other hand, is a polar elastomer produced from acrylonitrile and butadiene. The presence of acrylonitrile units gives NBR excellent resistance to oils, fuels, greases, and many hydrocarbon media. Therefore, it is widely used in fuel hoses, gaskets, O-rings, oil seals, gloves, diaphragms, and other components exposed to chemically aggressive or oil-rich environments. Nevertheless, NBR contains unsaturated butadiene segments and is generally less resistant than EPDM to ozone, UV radiation, long-term heat exposure, and oxidative aging. As a result, neither EPDM nor NBR alone can fully satisfy applications that require simultaneous resistance to oil, heat, ozone, aging, mechanical fatigue, and environmental degradation [1, 4–6].

Blending EPDM with NBR is therefore a technologically attractive route for designing multifunctional elastomeric materials. In principle, an EPDM/NBR blend can combine the oil and fuel resistance of NBR with the weathering, ozone, and thermal aging resistance of EPDM. Such a combination is especially relevant for automotive under-the-hood components, fuel-system seals, industrial gaskets, oil-field elastomeric parts, aerospace insulation systems, and chemical processing equipment. However, the development of high-performance EPDM/NBR blends is not straightforward because the two rubbers differ strongly in polarity, solubility parameters, molecular structure, and curing behavior [2, 3, 7].

The main challenge in EPDM/NBR blending is thermodynamic incompatibility. EPDM is essentially non-polar, whereas NBR is polar due to its acrylonitrile groups. This polarity mismatch usually leads to phase separation, coarse morphology, poor interfacial adhesion, non-uniform distribution of curatives, and weak stress transfer between the phases. As a result, uncompatibilized EPDM/NBR blends often show reduced tensile strength, inferior elongation, poor aging resistance, and unstable swelling behavior. The final properties are also affected by the EPDM/NBR ratio, acrylonitrile content in NBR, viscosity difference between the two rubbers, filler type, curing system, mixing procedure, and the location of additives in each phase [3, 6–9].

To overcome these limitations, several compatibilization strategies have been developed. One of the most widely studied approaches is the use of functionalized EPDM, especially maleic anhydride-grafted EPDM (MAH-g-EPDM). The introduction of maleic anhydride groups increases the polarity of the EPDM phase and improves its interaction with the polar NBR phase. This can reduce interfacial tension, refine phase morphology, improve filler dispersion, and enhance mechanical properties after aging. Similar effects have been reported for epoxidized EPDM, aminated epoxidized EPDM, and other reactive modifiers, where polar or chemically active groups promote stronger interphase interactions between EPDM and NBR [3, 10–13].

Reactive and semi-polar elastomers have also been investigated as compatibilizers or third-phase modifiers. For example, bromobutyl rubber (BIIR) can act as a link between EPDM and NBR due to its semi-polar nature and reactive bromine-containing sites. In peroxide- or sulfur-cured systems, BIIR may participate in crosslinking reactions and improve oil resistance, swelling resistance, fatigue behavior, and dimensional stability. More recent work has also examined chlorosulfonated polyethylene as a compatibilizer for EPDM/NBR blends, showing that the selection of a suitable interfacial modifier remains an active research direction rather than a solved problem [2, 13].

In parallel with chemical compatibilization, filler-assisted morphology control has become an important strategy for improving EPDM/NBR blend performance. Carbon black, silica, organoclay, montmorillonite, halloysite nanotubes, graphene oxide, carbon nanotubes, and hybrid nanofillers can influence not only reinforcement but also phase morphology, cure kinetics, swelling resistance, thermal stability, and barrier behavior. The effectiveness of these fillers depends strongly on their dispersion state, surface chemistry, aspect ratio, and preferential location in the EPDM phase, NBR phase, or interfacial region. For example, nanoclay and halloysite nanotubes can act as physical barriers against diffusion and thermal degradation, while graphene oxide and carbon nanotubes can introduce additional mechanical, thermal, and functional properties [7–16]. Recent EPDM/NBR/HNT studies have shown improvements in interfacial bonding, tensile strength, modulus, swelling resistance, and thermal stability when nanotubes are properly dispersed and combined with compatibilization strategies.

The curing system is another key factor controlling the performance of EPDM/NBR blends. Sulfur curing is commonly used because it provides good elasticity and mechanical strength, but sulfur crosslinks may be subject to reverse process or oxidative damage under severe thermal aging. Peroxide curing, especially with dicumyl peroxide, generally provides more thermally stable carbon–carbon crosslinks and better long-term heat resistance, although tensile properties may decrease if the formulation is not optimized. The balance between sulfur, peroxide, accelerator systems, and co-agents directly affects scorch time, optimum cure time, torque development, crosslink density, swelling behavior, and degradation kinetics [5, 17–19].

Thermal and oxidative aging remain central issues in EPDM/NBR blend design. When exposed to heat, oxygen, UV radiation, oil, or fuel, the rubber network may undergo chain breakage, additional crosslinking, embrittlement, plasticizer loss, and surface cracking. Compatibilizers and fillers can delay these processes by improving phase adhesion, reducing oxygen or solvent diffusion, stabilizing the crosslinked network, and promoting char formation at high temperatures. Therefore, for a meaningful evaluation of EPDM/NBR blends, not only tensile strength and hardness data are needed, but also data on ageing property retention, swelling behavior, thermal degradation temperature, activation energy, dynamic mechanical properties, fracture morphology, and performance characteristics under various conditions [1, 5, 14, 17–21].

For high-temperature and aerospace-related applications, EPDM/NBR blends can be further reinforced with short fibers, especially aramid fibers. In ablative environments, the material must resist erosion, cracking, heat penetration, and loss of integrity of the charred layer. Fiber orientation plays a major role in this behavior as it affects the density, porosity, hardness, and stability of the residual char layer. Properly oriented fibers can reduce erosion rate and improve thermal protection, making fiber-reinforced EPDM/NBR systems relevant for rocket motor insulation, thermal shields, flame-resistant barriers, and high-performance sealing applications [22].

Although considerable progress has been made, the literature on EPDM/NBR blends remains fragmented with regard to compatibilization chemistry, nanocomposite reinforcement, curing kinetics, aging studies, sealing perfor-

Table 1. Literature map of recent research directions in EPDM/NBR-based rubber blends

Research direction	Main focus	Materials / modifiers discussed	Key property improvement	Main research gap
EPDM/ NBR blend compatibility	Improving interfacial adhesion between non-polar EPDM and polar NBR	MAH-g-EPDM, Ep-EPDM, Am-Ep-EPDM, BIIR	Better phase dispersion, tensile strength, elongation, and aging resistance	More systematic comparison of compatibilizers under identical curing conditions is still needed
Reactive compatibilization	Formation of chemical or physical bridges between EPDM and NBR phases	Maleic anhydride, epoxy groups, amine-functionalized EPDM	Reduced phase separation and improved morphology	The long-term stability of reactive interfaces under oil, heat, and UV exposure remains insufficiently studied
Nanofiller reinforcement	Morphology control and mechanical/thermal enhancement	Organoclay, nanoclay, silica, carbon black, halloysite nanotubes	Higher modulus, improved thermal stability, increased crosslink density, better barrier properties	Excessive filler loading may cause agglomeration and property deterioration
Cure and degradation kinetics	Understanding vulcanization behavior and thermal degradation	Sulfur curing, peroxide curing, nanoclay-assisted curing	Shorter cure time, higher degradation onset temperature, improved network stability	More kinetic studies using modern modelling methods are required
Thermal aging and UV resistance	Retention of mechanical properties under harsh aging conditions	MAH-g-EPDM, Am-Ep-EPDM, BIIR-modified blends	Improved tensile retention, reduced cracking, better oxidative stability	Limited data are available on combined aging conditions such as heat + oil + UV
Ablation and fiber orientation	High-temperature resistance for aerospace applications	Short aramid fibers, EPDM/NBR composites	Stronger char layer, lower erosion rate, better flame resistance	More studies are needed on fiber–matrix adhesion and real service conditions
Industrial applications	Use of EPDM/NBR blends in demanding environments	Automotive seals, fuel hoses, gaskets, aerospace insulation, oil-resistant components	Combined oil resistance, ozone resistance, thermal stability, and durability	Scale-up, recyclability, and sustainability remain underdeveloped

mance, and ablation behavior. Many studies focus on one property group only, such as tensile strength, swelling, or thermal degradation, without connecting these results to morphology, interfacial structure, cure behavior, and practical service requirements. A broader review is therefore necessary to connect these separate research directions and provide a clearer structure–property–application relationship for EPDM/NBR-based rubber blends [14, 18, 24].

This review aims to provide a critical and updated discussion of recent advances in EPDM/NBR-based rubber blends, with emphasis on four connected aspects: interfacial compatibilization, filler-assisted morphology control, curing and degradation behavior, and application-specific performance. The review covers classical and recent studies on MAH-g-EPDM, epoxidized and aminated EPDM, BIIR, chlorosulfonated polyethylene, nanoclay, halloysite nanotubes, carbon black, graphene-based fillers, and fiber reinforcement. Special attention is given to how these modifiers affect phase morphology, crosslink density, mechanical strength, aging resistance, oil and solvent swelling, thermal stability, and ablation performance. By integrating diverse literature data rather than relying on a narrow set of studies, this review highlights the main design principles required for developing durable, multifunctional, and application-oriented EPDM/NBR elastomer systems. In contrast to narrowly focused discussions, this review compares EPDM/NBR blend systems with different

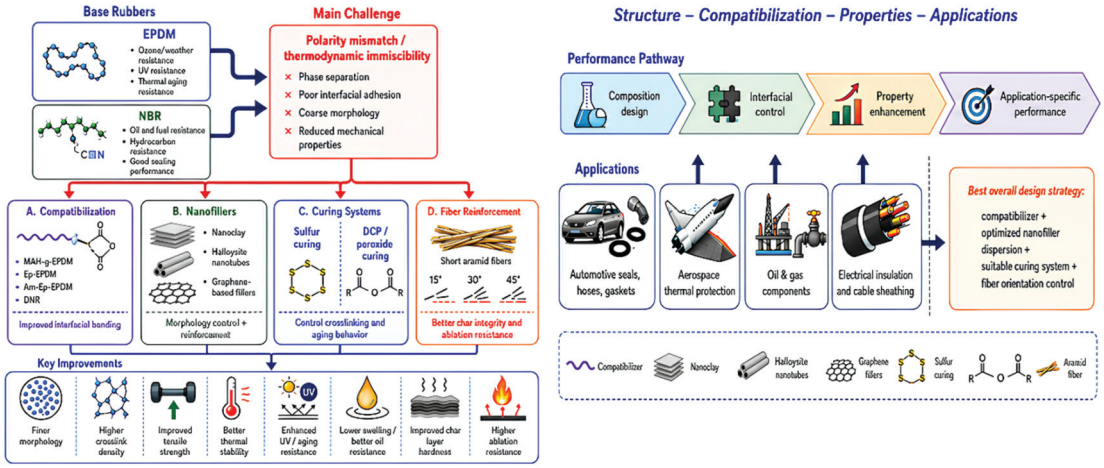

Fig. 1. Structure–compatibilization–property relationship and application-oriented design strategy for EPDM/NBR rubber blends

compatibilization routes, filler types, curing systems, aging environments, and application fields. This structure allows the reader to identify not only the advantages of each modification strategy but also their limitations, unresolved problems, and future research needs.

2. Compatibilization techniques and mechanisms

The inherent incompatibility between EPDM and NBR due to their different polarities and solubility parameters presents a major barrier in producing uniform and high-performance rubber blends. Without proper compatibilization, phase separation occurs, leading to weak interfacial adhesion, coarse morphology, and reduced mechanical and thermal properties. To overcome these issues, several chemical and physical compatibilization techniques have been explored, which facilitate interphase bonding and morphological stability. This section reviews the most effective compatibilization strategies employed for EPDM/NBR blends [8,15].

2.1 Maleic Anhydride Grafted EPDM (MAH-g-EPDM)

One of the most established compatibilizers is MAH-grafted EPDM, which involves grafting maleic anhydride groups onto the EPDM backbone. This modification introduces polar functional groups that can interact with the nitrile groups in NBR, enhancing interfacial adhesion through dipole–dipole and possibly covalent interactions.

Mechanism: The anhydride rings can undergo ring-opening reactions, reacting

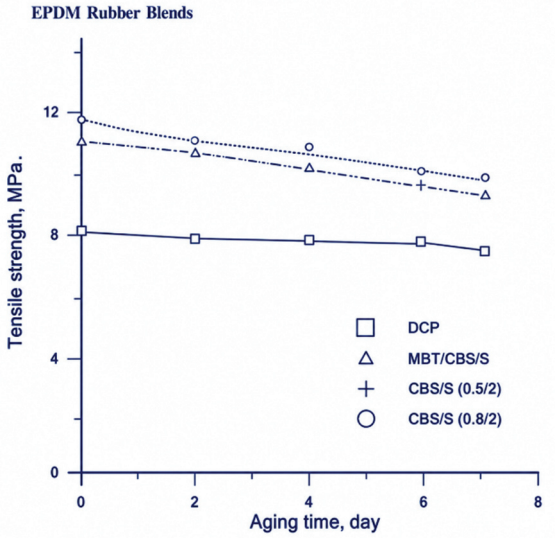

Fig. 2. Tensile strength vs. aging time, at 90C, of NBR=EPDM vulcanizates with different curing systems [3].

with amino or hydroxyl groups in the NBR phase or with co-curatives, forming covalent crosslinks across the interface.

Performance: Blends compatibilized with MAH-g-EPDM exhibit improved tensile strength, elongation, and thermal stability. The SEM images from experimental studies show finer dispersion and reduced domain size compared to uncompatibilized blends.

Additional Effect: MAH-g-EPDM also enhances the cure kinetics by participating in the vulcanization reaction, improving crosslink density and homogeneity [1-6,16].

Table 2. Comparison of compatibilizer systems for EPDM/NBR blends

Compatibilizer	Type	Mechanism	Effectiveness
MAH-g-EPDM	Chemical (grafted)	Dipole interactions, covalent bonding	High
Ep-EPDM	Chemical (oxidized)	Epoxy–nitrile interactions	Moderate
Am-Ep-EPDM	Chemical (aminated)	Amino–carbonyl and hydrogen bonding	Very High
BIIR	Reactive elastomer	Halogen bonding, peroxide crosslinking	High
Nanoclay + MAH	Physical & chemical	Interfacial stabilization + reinforcement	High
EVA / NR	Semi-polar elastomers	Miscibility enhancer	Low to Moderate

2.2 Epoxidized EPDM (Ep-EPDM) and Aminated Ep-EPDM (Am-Ep-EPDM)

Another effective strategy involves the epoxidation of EPDM, which introduces epoxy groups onto the polymer chain. These polar groups can form hydrogen bonds or chemical reactions with the nitrile segments in NBR. Further modification by introducing amine groups produces Am-Ep-EPDM, which significantly enhances compatibility [1-4, 19].

Ep-EPDM: Provides moderate improvement in phase dispersion and mechanical properties.

Am-Ep-EPDM: Shows superior compatibility, especially at 25/75 EPDM/NBR ratio, resulting in the highest mechanical strength, UV resistance, and long-term thermal aging performance.

Reactive Interface: The amine and epoxy groups react with carbonyl or double bonds in NBR or co-curatives, forming chemical bridges between the two phases.

2.3 Bromobutyl Rubber (BIIR) as a Tertiary Phase Compatibilizer

Bromobutyl rubber (BIIR) acts as both a compatibilizer and a reactive third-phase rubber. BIIR's semi-polar nature allows it to form hydrogen bonds or halogen bonding with both EPDM and NBR.

Mechanism: BIIR contains reactive allylic bromine sites, which can participate in peroxide- or sulfur-induced vulcanization, enhancing interfacial crosslinking [16-18].

Effects on Morphology: The addition of 10 phr BIIR significantly reduces domain separation and improves the overall blend homogeneity. Dynamic mechanical analysis (DMA) shows increased storage modulus and better fatigue resistance.

Swelling Resistance: BIIR-containing blends demonstrate lower oil absorption and better dimensional stability in aggressive fluid environments.

2.4 EVA, NR, and Polar Elastomer Blends

Although not as common as the methods described above, ethylene-vinyl acetate (EVA) and natural rubber (NR) have also been used in ternary blends to mediate compatibility. EVA's semi-polar character improves the miscibility to some extent, and NR provides elasticity. However, their compatibilization efficiency is generally lower compared to MAH-g-EPDM and Am-Ep-EPDM.

2.5 Physical Compatibilization and Filler-Assisted Interface Control

Apart from chemical modifications, nanofillers such as nanoclay, silica, or carbon black can serve as morphology stabilizers, especially when surface-treated with functional groups.

Mechanism: Fillers are predominantly located at the EPDM/NBR interface, reducing interfacial tension and acting as physical compatibilizers [9, 17-20].

Combination with MAH: When used in conjunction with MAH, these fillers improve both phase adhesion and reinforcement, leading to better mechanical and thermal properties.

2.6. Critical Comparison of Compatibilization Strategies

Although several compatibilization strategies have been proposed for EPDM/NBR blends, their effectiveness depends strongly on the blend ratio, curing system, filler type, and processing conditions. MAH-g-EPDM is one of the most practical compatibilizers because it

Table 3. The critical role of the curing system in the thermal aging behavior of EPDM/NBR blends [4]

Curing System	Advantages	Disadvantages
Sulfur	Higher mechanical strength, lower cost	Lower aging resistance, prone to reversion
Dicumyl Peroxide (DCP)	Superior thermal stability, better long-term aging	Lower tensile strength if not optimized
Curing System	Advantages	Disadvantages

improves polarity balance and interfacial adhesion without completely changing the elastomeric nature of the blend. However, its efficiency may be limited if grafting level, dispersion, or curing conditions are not optimized. Epoxidized and aminated EPDM provide stronger interfacial interactions, but they may require additional synthesis steps, which can increase processing complexity.

BIIR and other reactive elastomers are useful because they can act as flexible interfacial bridges between EPDM and NBR. Their advantage is that they improve both compatibility and oil resistance, especially in peroxide-cured systems. However, excessive addition may change the final hardness, elasticity, or cost of the material. In contrast, EVA and NR can provide partial improvement in miscibility, but their compatibilization efficiency is usually lower than chemically functionalized EPDM-based systems.

From a practical point of view, the most promising strategy is not the use of a single modifier, but the combination of chemical compatibilization with controlled filler dispersion and optimized curing. Such combined systems provide better morphology, stronger interfacial bonding, higher crosslink density, and improved resistance to aging and swelling. Therefore, future studies should focus more on hybrid compatibilization systems rather than isolated additives.

3. Thermal stability and aging performance

One of the most critical factors affecting the long-term functionality of elastomeric materials is their thermal stability and resistance to aging mechanisms, including oxidative degradation, UV exposure, and thermal oxidative crosslinking or chain break. In EPDM/NBR blends, aging behavior is influenced by both the intrinsic properties of the base polymers and the type of compatibilizer or additive used.

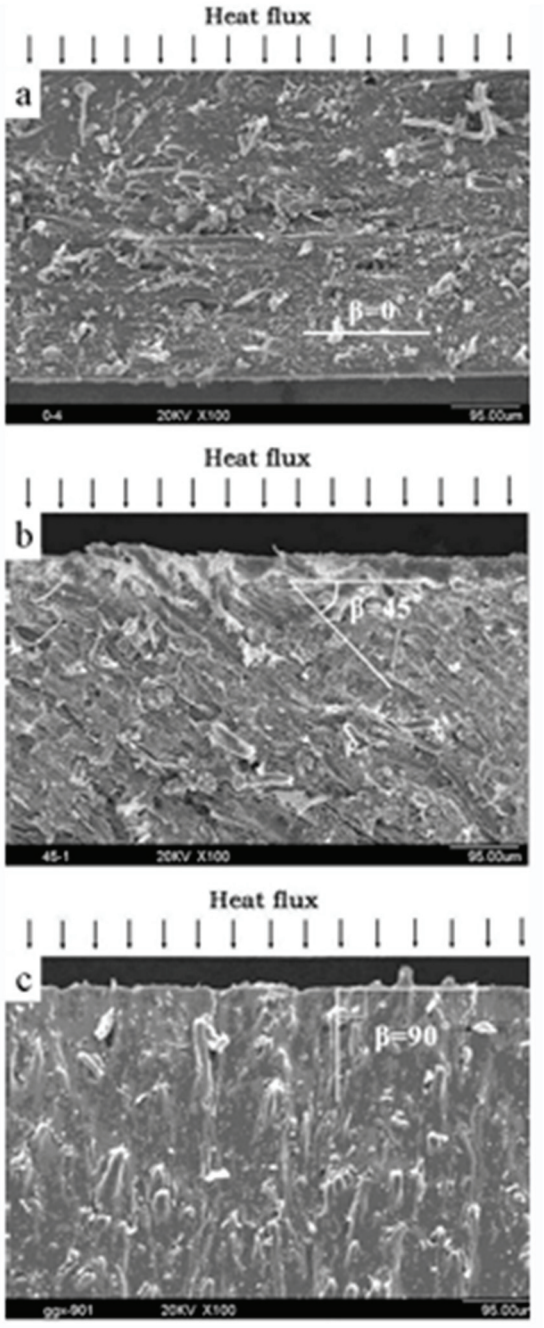

Fig. 3. Fiber orientation in the virgin specimens [4].

Table 4. Thermal stability, aging resistance and UV performance of compatibilized EPDM/NBR blends

Blend Type	Initial Degradation Temp (°C)	Tensile Retention After Aging (%)	UV Resistance	Char Residue (%)	Overall Thermal Performance
EPDM/NBR (No Compatibilizer)	280–300	45–55	Poor	10–12	Low
EPDM/NBR + MAH-g-EPDM	~350	~80	Good	15–18	High
EPDM/NBR + Am-Ep-EPDM	~360	85–90	Excellent	18–20	Very High
EPDM/NBR + BIIR	~340	~75 (in oil)	Moderate	12–14	High in oil environments
EPDM/NBR + MAH + Nanoclay	~370	~85	Good	20–22	Excellent

3.1 Thermal Degradation Profiles

Thermogravimetric analysis (TGA) has shown that pure EPDM typically begins to thermally decompose above 320°C, whereas NBR starts degrading in a slightly lower range (~280–300°C) due to the presence of unsaturated butadiene segments in its composition. When blended, the thermal stability of EPDM/NBR systems strongly depends on phase compatibility and crosslinking density [4,5,12, 48].

Without Compatibilizer: EPDM/NBR system exhibits two-step degradation behavior, with weak interfacial adhesion. The degradation temperatures correspond to the individual decomposition of EPDM and NBR phases. It shows a broad degradation profile and reduced thermal integrity.

With MAH-g-EPDM Compatibilizer: The onset of degradation shifts to higher temperatures (~350°C). A more compact char structure is produced due to enhanced crosslinking. Single-phase degradation curve is observed in some blends, indicating improved miscibility.

With Am-Ep-EPDM Compatibilizer: Even higher thermal stability due to enhanced interfacial reactions is shown [17, 37, 41]. Char residue increases, indicating slower degradation kinetics and more robust network structures.

3.2. Influence of sulfur and peroxide curing systems on the thermal aging behavior of EPDM/NBR Blends

Sulfur-cured blends exhibit earlier degradation but better elasticity under mild aging conditions, while DCP-cured blends demonstrate superior thermal stability and improved long-term aging resistance. Therefore, sulfur curing may be more suitable for applications requiring flexibility and cost efficiency, whereas peroxide curing is preferable for EPDM/NBR blends exposed to high-temperature or prolonged oxidative environments.

Sulfur-cured blends exhibit earlier degradation but better elasticity under mild aging conditions.

3.3 Aging Under UV and Air Exposure

Accelerated aging experiments (e.g., UV chamber, hot air oven) show significant differences in retention of mechanical properties.

MAH-g-EPDM-based blends: Retention of ~80% of original tensile strength after 72h at 150°C [18-21]. SEM analysis shows fewer cracks and smoother surface morphology after UV exposure.

Am-Ep-EPDM-based blends: The highest retention of elongation and tear resistance. The amino groups act as radical scavengers, mitigating oxidative degradation [45-49].

BIIR-modified blends: Performance is better under aging conditions in oils and liquids, but somewhat less stable under high UV conditions. Improved resistance to swelling by brake fluid and engine oil has been demonstrated, ensuring dimensional stability.

3.4 Thermo-Mechanical Aging (DMA and TMA Analysis)

Dynamic mechanical analysis (DMA) shows that the elastic modulus (E') of the compatibilized blends remains high even after thermal aging. The loss tangent (damping behavior) is lower in MAH and BIIR blends, indicating tighter crosslinked networks. The glass transition temperature (T_g) changes little after aging, indicating stable morphology [24, 49, 54].

Table 5. Three main morphological forms demonstrating the efficiency of nanoclay depending on its dispersion in the polymer matrix

Dispersion Type	Structure	Property Impact	Dispersion Type
Intercalated	Clay galleries expand	Moderate reinforcement	Intercalated
Exfoliated	Individual layers dispersed	Maximum reinforcement and surface area	Exfoliated
Agglomerated	Clays form clusters	Decreased performance, stress points	Agglomerated

3.5 Char Structure and High-Temperature Residue

TGA residue studies and flame-ablation testing (relevant for aerospace applications) show that nanoclay- and MAH-filled systems form a stronger, more compact char layer. In fiber-reinforced systems, increasing the fiber angle enhances surface hardness, helping reduce char erosion at elevated temperatures (~2000°C flame exposure).

Thermal stability and aging resistance of EPDM/NBR blends are significantly enhanced through proper compatibilization and curing strategies. MAH-g-EPDM and Am-Ep-EPDM not only improve interfacial bonding but also suppress thermal degradation and UV-induced embrittlement [22-24].

DCP curing technology outperforms sulfur-based technology under long-term aging conditions, while the addition of nanofiller provides char strength and additional barrier protection. Together, these approaches extend the service life of EPDM/NBR blends in high-temperature, oxidative, and chemically aggressive environments [39, 49, 53].

4. Nanofiller effects and morphology control

The incorporation of nanofillers into polymer blends has become a powerful strategy to improve mechanical, thermal, and environmental resistance properties by manipulating the material internal structure and interfacial interactions. In EPDM/NBR rubber blends, nanoclay (organically modified montmorillonite, e.g., Cloisite 20A, 30B) has been particularly effective in enhancing morphology control, phase dispersion, and crosslinking characteristics, especially when used in conjunction with compatibilizers.

4.1 Role of Nanoclay in EPDM/NBR Systems

Nanoclay platelets have a high aspect ratio and large surface area, which allows them to act both as reinforcing agents and morphological stabilizers.

Interfacial Reinforcement: Nanoclay can be localized at the EPDM/NBR interface, reducing interfacial tension and improving phase adhesion [11, 44, 53].

Barrier Effect: Due to their layered silicate structure, nanoclays hinder diffusion of small molecules, improving resistance to solvents and oxidative gases.

Thermal Shielding: Nanoclay forms an insulating char layer during degradation, increasing the thermal decomposition temperature.

4.2 Dispersion and Morphology Control

SEM and XRD analysis revealed that that the addition of 2 phr nanoclay in MAH-g-EPDM/NBR blends resulted in the formation of exfoliated structures, while higher concentrations (5–7 phr) caused partial agglomeration, reducing the efficiency.

4.3 Effect on Cure Behavior

Nanoclay significantly influences cure kinetics due to its interaction with curatives and the polymer matrix:

Accelerated Cure Rate: Clay particles catalyze crosslinking reactions, reducing scorch time (t_{s2}) and optimum cure time (t_{c90}).

Crosslink Density: Swelling tests show increased crosslink density in nanoclay-filled blends.

Activation Energy: TGA-based kinetic studies demonstrate that nanoclay lowers the activation energy for curing and increases it for decomposition, indicating faster curing and slower thermal decomposition [31, 39, 46].

Table 6. Comparative influence of nanoclay content and compatibilization on the morphological, thermal, and mechanical properties of EPDM/NBR rubber blends

Formulation	Nanoclay Loading	Morphology	Thermal Stability	Mechanical Strength
EPDM/NBR (No nanoclay)	0 phr	Coarse	Baseline	Moderate
EPDM/NBR + 2 phr Nanoclay	Intercalated/ Exfoliated	Fine/mixed	+20–30 °C	+15–20%
EPDM/NBR + 5–7 phr Nanoclay	Agglomerated	Heterogeneous	Variable	Decreased (stress points)
EPDM/NBR + MAH + 2 phr Nanoclay	Exfoliated	Compact/ Uniform	+40 °C	Excellent

4.4 Thermal and Mechanical Enhanment

Blends containing nanoclay exhibit:

- Higher tensile strength and modulus due to particle reinforcement;
- Improved thermal stability, with onset degradation temperatures shifted by +20 to +40°C compared to neat blends;
- Greater dimensional stability in hot oil and fuel environments;
- Improved radiation resistance, likely due to layered barrier protection from silicates.

4.5 Compatibilizer–Nanoclay Synergy

When used together with compatibilizers like MAH-g-EPDM:

- Nanoclay dispersion improves, reducing agglomeration;
- The interface between EPDM and NBR becomes smoother, as can be seen in SEM images (e.g. fewer phase boundaries, more continuous matrix);
- Enhanced balance between stiffness and elasticity is achieved [12, 31, 48].

4.6. Recent Nanofillers Beyond Canoclay

Recent studies show that the reinforcement of EPDM/NBR blends is no longer limited to conventional nanoclay systems. Halloysite nanotubes have attracted attention due to their tubular morphology, high aspect ratio, and ability to improve both mechanical strength and swelling resistance. Graphene oxide and carbon nanotubes are also promising, since they can enhance thermal conductivity, barrier properties, mechanical reinforcement, and, in some cases, electrical or sensing performance. Silica and carbon black remain industrially important fillers due to their availability, reinforcing efficiency, and compatibility with existing rubber-processing technologies.

However, these fillers also present challenges. Graphene-based fillers and CNTs can agglomerate easily if their surface is not properly modified. Halloysite nanotubes require good dispersion to achieve effective reinforcement. Silica often needs coupling agents to improve rubber–filler interaction. Therefore, the performance of nanofilled EPDM/NBR blends depends not only on filler type, but also on surface chemistry, filler loading, dispersion method, and interaction with the curing system [36, 41].

The integration of nanoclay into EPDM/NBR blends, particularly when combined with chemical compatibilizers like MAH-g-EPDM, significantly enhances morphology control and overall performance. Optimal filler loading (around 2 phr) results in improved cure rate, thermal resistance, mechanical reinforcement, and long-term durability. However, excessive loading must be avoided due to agglomeration risks. Synergy between nanofiller dispersion and interfacial compatibility is a key factor in the development of next-generation elastomer nanocomposites for challenging applications.

5. Ablation resistance and fiber orientation effects

In high-temperature environments such as aerospace propulsion systems, solid rocket motors, and thermal insulation applications, ablation resistance, a key parameter is ablation resistance, which is the ability of a material to resist surface erosion caused by extreme heat flow. EPDM/NBR blends, despite their mechanical strength, require additional reinforcement to withstand such conditions. Reinforcing these elastomers with short aramid fibers significantly improves their resistance to thermal degradation and ablation by promoting char layer formation and stability.

Table 7. Influence of fiber angle on ablation resistance and char layer properties of composite specimens

Fiber Angle	Erosion Rate (mm/s)	Char Layer Hardness (Shore D)	Porosity (%)	Observation
15°	Highest (~0.39)	Lowest (~48)	High	Weak structure, more cracks
30°	Moderate (~0.29)	Moderate (~58)	Medium	Balanced erosion vs. strength
45°	Lowest (~0.21)	Highest (~66)	Low	Best char integrity, compact surface

5.1 Principle of Fiber Reinforcement in Ablative Composites

The addition of short aramid fibers into EPDM/NBR matrices offers many benefits [11, 16, 18, 52]:

Enhanced Char Layer Integrity: Fibers act as a skeletal framework within the polymer, maintaining structure during thermal decomposition.

Improved Thermal Barrier: Fibers slow down heat penetration, lowering the back-face temperature.

Controlled Erosion Rate: Fibers reduce melt flow and surface cracking under flame exposure [14, 22, 34].

5.2 Effect of Fiber Orientation Angle

The orientation angle (θ) of fibers relative to the ablation surface is a critical design parameter. Experimental results (from nbr epdm 2.pdf) using 15°, 30°, and 45° orientations under oxy-acetylene flame (~2000 °C) showed distinct trends (Table 7).

Increasing the fiber angle improves the compactness of the residual char layer, enhances its hardness, and reduces surface porosity, which leads to lower erosion rates and better ablation resistance [4, 37, 45, 59].

5.3 Surface Morphology and SEM Analysis

SEM micrographs reveal that at higher orientation angles, fibers are better aligned against flame penetration, forming denser char structures. At lower angles (15°), fibers lie more parallel to the flame, allowing easier gas penetration and crack propagation. EPDM/NBR composites with 45° fiber orientation show fewer voids, minimal delamination, and uniform surface morphology after exposure [6,14, 27, 51].

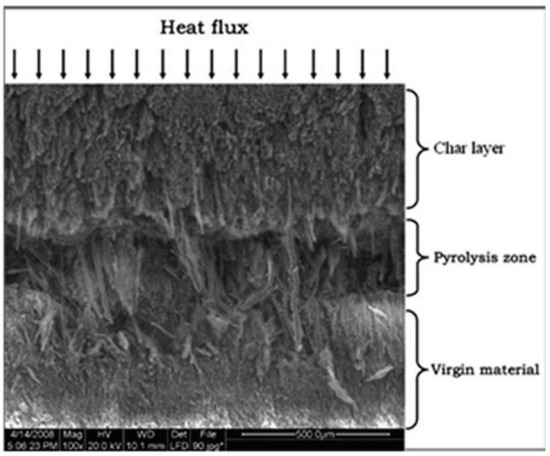

Fig.4. Longitudinal section of the ablated sampels as β is 90°C [4]

5.4 Fiber–Matrix Interface and Thermal Stability

The interface between aramid fibers and the EPDM/NBR matrix is also strengthened through compatibilizers (e.g., MAH), which help form better chemical or physical adhesion, reducing fiber pull-out during ablation. TGA and post-ablation residue analysis confirm that 45° fiber alignment leads to higher char yield (~38%) compared to lower angles (~25%). Improved residue correlates with longer operational lifetimes in flame environments.

5.5 Applications

These findings make fiber-oriented EPDM/NBR composites ideal candidates for:

- Solid rocket motor insulation liners;
- Missile nose cones;
- Thermal shielding panels in aerospace;
- High-performance flame-resistant gaskets and barriers.

6. Fiber orientation and thermal performance

The fiber orientation in EPDM/NBR blends is a critical factor in optimizing their performance under high thermal loads. Increasing the fiber angle enhances the structural integrity of the char layer, reduces thermal erosion, and improves insulation characteristics. When combined with effective compatibilization and optimized curing, fiber-reinforced EPDM/NBR systems become highly suitable for advanced thermal protection applications [17-19, 32, 60].

Cure and Degradation Kinetics

The performance and durability of rubber composites such as EPDM/NBR blends depend significantly on their cure kinetics (vulcanization behavior) and thermal degradation kinetics [22-26]. These processes govern the formation and stability of the polymer network, thereby affecting mechanical strength, chemical resistance, and long-term performance under thermal or oxidative stress. A thorough understanding of these kinetic processes is essential for optimizing processing parameters and predicting service life.

6.1 Cure Kinetics

Vulcanization involves the formation of a crosslinked 3D network through heat-induced chemical reactions, which are typically measured using oscillating disk rheometry and analyzed using kinetic models.

Rheometric Observations [2]

Cure curves exhibit sigmoidal behavior with defined scorch time (t_{s2}) and optimum cure time (t_{c90}). EPDM/NBR blends containing 2 phr nanoclay and MAH-g-EPDM show:

- Decreased t_{s2} and t_{c90} → faster cure initiation and completion;
- Increased maximum torque → higher crosslink density [2, 29].

Kinetic Modeling:

Cure reactions were evaluated using first-order kinetic interpretation. The synergistic effect of nanoclay and MAH-g-EPDM catalyzes the crosslinking reaction, promoting faster and more complete network formation.

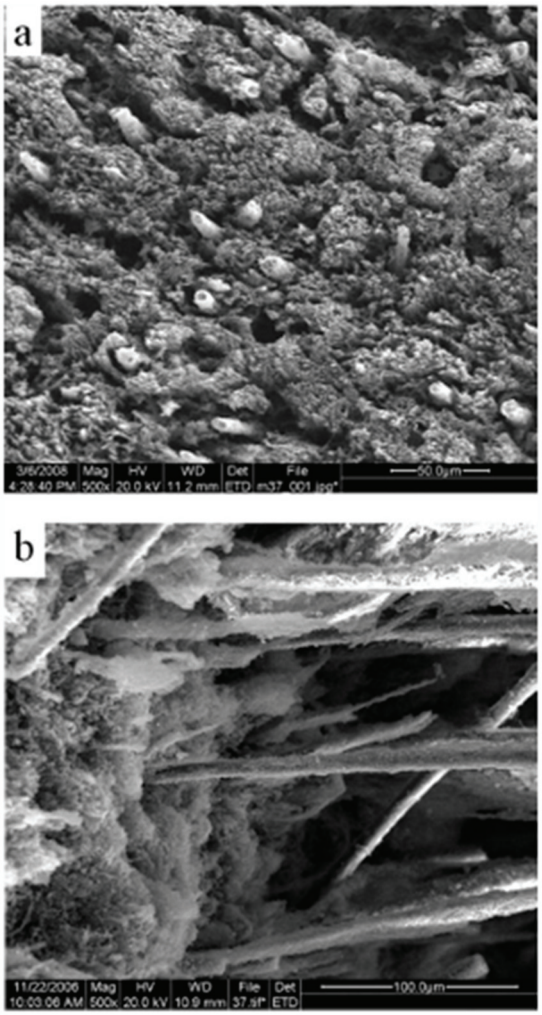

Fig. 5. Fibrous morphology of aramid fiber safter ablated as ß is 90°C. (a) in the char layer surface and (b) drawn out from virgin material [4, 21].

Models (Kamal–Sourour and Arrhenius equations):

Reaction order (n): ~1.0 for most blends → pseudo-first-order behavior.

Activation energy (E_a):

- Neat blend: ~65 kJ/mol;

Table 8. Influence of Fiber Angle on Ablation Performance of Composite Specimens

Property	No Fiber	15° Fiber	30° Fiber	45° Fiber
Erosion Rate	~0.50 mm/s	~0.39 mm/s	~0.29 mm/s	~0.21 mm/s
Char Hardness (Shore D)	~40	~48	~58	~66
Surface Porosity	High	High	Medium	Low
Ablation Resistance	Poor	Moderate	Good	Excellent

Table 9. Effect of MAH-g-EPDM compatibilizer and nanoclay reinforcement on cure time, scorch time, and maximum torque of EPDM/NBR blends

Formulation	ts2 (min)	tc90 (min)	Max Torque (dN·m)
Neat EPDM/NBR	3.8	8.5	7.2
+ MAH-g-EPDM	3.2	7.1	8.6
+ MAH-g-EPDM + 2 phr NC	2.7	6.3	9.8

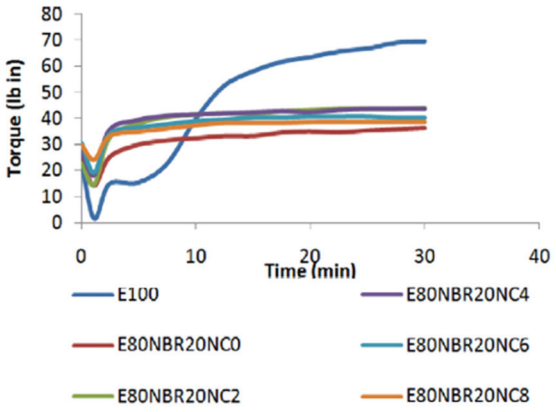

Fig. 6. Cure curves for various EPDM-NBR blends [2, 7, 18]

- With nanoclay: ~55 kJ/mol → Easier initiation

- With nanoclay + MAH: ~48 kJ/mol → Fastest curing\

6.2 Degradation Kinetics

Thermal degradation behavior was assessed via thermogravimetric analysis (TGA) and model-fitting methods [2-10].

Degradation Profile:

EPDM/NBR blends exhibit two-step degradation:

- NBR phase decomposition (~280–350 °C)

- EPDM phase decomposition (~350–480 °C)

Effect of Nanoclay and Compatibilizers:

Incorporation of 2 phr nanoclay increases degradation onset by +30–40°C.

Activation energy for degradation increases:

Neat blend: ~140 kJ/mol

nanoclay: ~165 kJ/mol

nanoclay + MAH: ~178 kJ/mol

Nanoclay acts as a thermal barrier and char promoter. MAH improves interfacial adhesion, reducing chain scission probability and enhancing degradation resistance [29, 61].

6.3 Crosslink Density and Network Structure

Crosslink density, calculated via swelling tests (Flory–Rehner equation), further validates the kinetic results. Nanoclay and compatibilizers increase network tightness, reducing solvent uptake and enhancing mechanical stability at elevated temperatures. DSC measurements confirm higher glass transition temperatures (T_g) in modified blends, indicating stiffer matrices [34, 44, 56].

6.4 Summary of Cure and Degradation Behavior

The kinetics of vulcanization and degradation in EPDM/NBR blends are highly sensitive to the presence of nanofillers and compatibilizers. Although nanoclay accelerates cure rates and improves thermal resistance, its effect is maximized when used with polar compatibilizers like MAH-g-EPDM. These modifications reduce activation energies for curing while increasing the activation energy for degradation, resulting in elastomers with faster processing, improved thermal durability, and superior long-term stability [22, 40-44].

Table 10. Thermal degradation and activation energy of EPDM/NBR nanocomposites

Formulation	T_{onset} (°C)	T_{max} (°C)	E_a (kJ/mol)
Neat EPDM/NBR	~280	~445	~140
+ Nanoclay	~310	~455	~165
+ Nanoclay + MAH-g-EPDM	~325	~460	~178

Table 11. Comparative cure and degradation behavior of EPDM/NBR nanocomposites

Property	Neat EPDM/NBR	Nanoclay	Nanoclay + MAH
Cure Time (tc90)	High (slow)	Moderate	Low (fast)
Cure Activation Energy	~65 kJ/mol	~55 kJ/mol	~48 kJ/mol
Degradation Onset Temperature	~280 °C	~310 °C	~325 °C
Degradation Activation Energy	~140 kJ/mol	~165 kJ/mol	~178 kJ/mol
Crosslink Density	Low	Medium	High

Table 12. Comparative functional performance of EPDM, NBR, and modified EPDM/NBR blends

Property	**EPDM**	**NBR**	**EPDM/NBR Blend (Modified)**
Oil Resistance	✗	✓	✓✓
Ozone & UV Resistance	✓✓	✗	✓✓
Thermal Stability	✓✓	✓	✓✓✓
Mechanical Strength	✓	✓✓	✓✓✓
Aging in Harsh Environments	✗	✗	✓✓

7. Applications and future directions

7.1 Industrial Applications of EPDM/NBR Composites

Due to their complementary properties, EPDM and NBR rubbers, especially when compatibilized and reinforced with nanofillers or fibers, find applications in several demanding industries. Each modification strategy – whether through chemical compatibilizers, nanoclay, or fiber reinforcement – allows the composite to be tailored to the specific requirements of the end application.

Automotive Industry

EPDM/NBR blends are used in engine mounts, fuel hoses, gaskets, O-rings, and sealing systems. NBR phase provides fuel and oil resistance, while EPDM contributes ozone and heat resistance. Nanoclay-reinforced EPDM/NBR shows enhanced dimensional stability and reduced oil absorption, critical for under-the-hood parts exposed to aggressive fluids and elevated temperatures [21-26, 62].

Aerospace and Defense

Fiber-reinforced EPDM/NBR composites are employed in solid rocket motor insulation, missile nose cones, and thermal shields [59]. High ablation resistance, especially in 45° fiber orientation systems, enables survival in ~2000 °C flame environments. Aramid fibers and optimized char formation improve material integrity during supersonic thermal stress.

Oil and Gas Sector

NBR-rich blends dominate in applications such as drilling equipment seals, oil-resistant gloves, and pipe linings. Modified EPDM/NBR systems with BIIR or MAH-g-EPDM offer improved resistance to sour gases, hydrocarbons, and hydraulic fluids [54].

Electrical and Sealing Applications

EPDM/NBR blends used in weatherproof seals, cable sheathing, and electrical insulation offer the ozone resistance of EPDM and the flexibility of NBR. Nanoclay or silica fillers improve dielectric strength and creep resistance.

7.2 Advantages over Traditional Single Rubbers

7.3 Future Research Directions

Despite major advancements, several challenges and open areas remain:

1. *Reactive compatibilization without toxic byproducts*

Green chemistry approaches such as bio-based functional groups or peroxide-free compatibilization should be explored. The formation of compatibilizers in situ during the mixing process could reduce the number of processing steps [51-54].

2. *Functional nanofillers beyond clay*

The use of advanced nanomaterials such as:

- graphene oxide for thermal conductivity;
- carbon nanotubes (CNTs) for strength and electrical properties;
- halloysite nanotubes for fire resistance [24, 28, 57].

Use of advanced nanomaterials like:

- Graphene oxide for thermal conductivity;
- Carbon nanotubes (CNTs) for strength and electrical response;
- Halloysite nanotubes for flame resistance [24, 28, 57].

These can enable multifunctional properties such as self-healing, EMI shielding, or real-time damage sensing [28].

3. *Additive Manufacturing and Smart Processing*

Research into 3D-printable EPDM/NBR composites can expand design freedom for aerospace and medical applications. Smart curing systems using microwave or photothermal triggers may reduce energy consumption.

4. *Sustainability and Recycling*

EPDM/NBR blends are difficult to recycle due to their crosslinked nature. Devulcanization, reprocessing additives, or biodegradable filler systems may provide sustainable disposal routes.

5. *Multi-Scale Modeling and Digital Twin Integration*

Using computational simulations and machine learning to optimize blend compo
sition, cure profile, and failure prediction could reduce experimental effort.

7.4. Current Research Gaps

Despite the significant progress in EPDM/NBR-based rubber blends, several research gaps remain. First, many studies focus mainly on tensile strength and hardness, while fewer works provide a complete connection between morphology, crosslink density, swelling behavior, and long-term aging performance. Second, the effect of compatibilizers is often studied separately from the curing system, although both factors strongly influence the final network structure. Third, nanofiller-based studies frequently report improved properties, but the role of filler localization at the EPDM/NBR interface is still not fully clarified.

Another important limitation is the lack of standardized aging conditions. Different studies use different temperatures, exposure times, oils, solvents, and UV conditions, making direct comparison difficult. In addition, most studies remain at laboratory scale, while industrial processing, cost, recyclability, and long-term service prediction are less frequently discussed. Future research should therefore combine experimental characterization with modeling, digital process control, and sustainability assessment in order to develop EPDM/NBR blends that are both technically effective and industrially realistic [51-56, 63].

EPDM/NBR composites have evolved from basic binary blends into engineered multifunctional materials capable of meeting the performance demands of automotive, aerospace, oil, and electrical industries. Through compatibilization, nanotechnology, and strategic reinforcement, these elastomers now demonstrate remarkable resistance to oil, weathering, ablation, and thermal degradation. Future progress lies in eco-friendly formulation, multifunctional filler development, and digitally assisted design to unlock their full potential in emerging technologies [58, 63].

Conclusion

The development of high-performance EPDM/NBR rubber blends is strongly dependent on the successful control of interfacial compatibility, morphology, curing behavior, and reinforcement strategy. This review shows that EPDM and NBR possess complementary properties: EPDM provides excellent resistance to ozone, weathering, and thermal aging, whereas NBR offers superior oil, fuel, and hydrocarbon resistance. However, their direct blending is limited by polarity mismatch and thermodynamic immiscibility, which can lead to phase separation, poor interfacial adhesion, and reduced mechanical performance.

Recent studies demonstrate that compatibilization is the most effective approach for overcoming these limitations. Functionalized modifiers such as MAH-g-EPDM, Ep-EPDM, Am-Ep-EPDM, and BIIR improve interfacial bonding, refine phase morphology, and enhance the retention of mechanical properties under thermal and oxidative aging. In addition, nanofillers, particularly nanoclay, halloysite nanotubes, graphene-based fillers, silica, and carbon black, contribute to better morphology control, higher crosslink density, improved thermal stability, and stronger barrier properties. Their effectiveness depends on filler dispersion, surface chemistry, loading level, and interaction with the curing system.

The review also highlights that curing systems play a decisive role in ensuring long-term performance. Sulfur curing provides good elasticity and mechanical strength, while peroxide curing offers better thermal stability and aging resistance due to the formation of more stable carbon–carbon crosslinks. For high-temperature and aerospace-related applications, short aramid fiber reinforcement further improves ablation resistance by strengthening the char layer, reducing porosity, and lowering erosion rate. In particular, optimized fiber orientation contributes significantly to thermal protection and structural stability under severe flame exposure.

Overall, EPDM/NBR blends can be transformed into advanced multifunctional elastomeric materials through the combined use of compatibilizers, optimized nanofiller dispersion, suitable curing systems, and structural reinforcement. These materials show strong potential for automotive seals, fuel hoses, gaskets, cable insulation, oil-resistant components, and aerospace thermal protection systems. Future research should focus on eco-friendly compatibilization, advanced functional nanofillers, digital process control, long-term service-life prediction, and sustainable recycling strategies. Such developments will support the design of durable, application-specific, and environmentally responsible EPDM/NBR-based rubber composites.

List of symbols

Abbreviation	Full Form
EPDM	Ethylene Propylene Diene Monomer
NBR	Nitrile Butadiene Rubber
MAH-g-EPDM	Maleic Anhydride Grafted EPDM
Ep-EPDM	Epoxidized EPDM
Am-Ep-EPDM	Aminated Epoxidized EPDM
BIIR	Bromobutyl Rubber
DCP	Dicumyl Peroxide
EVA	Ethylene Vinyl Acetate
NR	Natural Rubber
TGA	Thermogravimetric Analysis
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimetry
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction
Tg	Glass Transition Temperature
ts2	Scorch time (rheometric parameter)
tc90	Optimum cure time
Ea	Activation Energy
phr	Parts per hundred rubber
UV	Ultraviolet
FTIR	Fourier Transform Infrared Spectroscopy
CNT	Carbon Nanotube
EMI	Electromagnetic Interference
RCF	Rolling Contact Fatigue
PCA	Principal Component Analysis
GPS	Global Positioning System
STFT	Short-Time Fourier Transform
SK	Spectral Kurtosis

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