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PVC vs. PE vs. EPR: A Comprehensive Review of Cable Insulation Performance in Fire and Service Conditions

Harshit Ray[1], Tejsingh Patle[2], Dinesh Matangi[3], Dhiraj Sharma[4], Nathan Khobragade[5], Rudrasinh Vaghela[6]
Department of Fire Engineering, National Fire Service College, Rajnagar, Nagpur- 440013

Abstract: This review evaluates the fire dynamics, operational limits, and environmental profiles of PVC, PE, and EPR cable insulations, synthesising data from cone calorimetry (ISO 5660), vertical flame tests (IEC 60332), and thermogravimetric analysis. PVC achieves the lowest peak heat release rate (PHRR: 200–400 kW/m²) and an LOI of 20–25%, primarily via endothermic dehydrochlorination and gas-phase radical scavenging by HCl [1][7][8]. This fire-retardant advantage, however, incurs the highest smoke density (1,000–1,500 m²/kg) and corrosive HCl emissions, with a continuous service ceiling of 90°C [5][7]. PE exhibits superior dielectric properties (εr ≈ 2.3) but fails critically in fire scenarios: PHRR exceeds 1,000 kW/m², heat of combustion reaches 43–46 MJ/kg, flame spread rates of 5–15 mm/s, and char yield below 5%, rendering it inherently flammable with no protective residue [9][10]. EPR provides the best thermal endurance (service up to 105°C, peak 150°C) and balanced fire performance—intermediate PHRR (400–700 kW/m²), char yield of 10–30% (enhanced by inorganic fillers), and lowest smoke production (400–800 m²/kg)—without halogenated byproducts [2][4][6].

Material selection remains inherently application-specific: PVC for cost-driven, low-fire-risk installations; PE only where electrical performance is paramount, and fire mitigation is externally enforced; EPR for high-temperature or safety-critical environments [5][6][9]. The review further identifies emerging technical pathways—AI-driven early-warning systems, nanofillers, hybrid flame retardants, and halogen-free formulations—as key to decoupling fire resistance from environmental toxicity in next-generation cable systems [12].

Keywords: Polymeric cable insulation; PVC; PE; EPR; fire behaviour; heat release rate; cone calorimetry; IEC 60332; flame spread; smoke toxicity; char formation; halogen-free; nano-additives; AI fire prediction; thermal stability

I. INTRODUCTION

A. Fire Hazards Due to Electrical Cables

Electrical cables are fundamental to modern power distribution and control systems across residential, commercial, industrial, and transportation sectors. Despite their essential role, these components pose significant fire hazards; electrical fires account for approximately 60% of total fire accidents in many regions, and cable-related incidents cause substantial casualties and property damage [1].

The inherent fire risk stems from multiple factors: insulation degradation with age, overloading conditions generating excessive heat beyond thermal stability limits, short circuits producing intense localised heating and arcing, and environmental stresses including moisture, chemical exposure, UV radiation, and mechanical damage that accelerate insulation deterioration [2][3].

High-risk environments such as nuclear power plants, thermal power stations, chemical facilities, and underground utility tunnels face particularly severe consequences. Cable fires can trigger hydrogen explosions in nuclear facilities, volatile substance explosions in chemical plants, oil-immersed transformer fires in power stations, and threaten critical infrastructure in urban utility tunnels [3][4].

B. Cable Fires: Mechanisms and Consequences

Cable fires initiate through several mechanisms: overheating causing gradual thermal degradation, partial discharges creating localised hot spots, and external heat sources [5]. Once ignited, flame fronts advance along cable runs through convective heating from the flame, radiative heat transfer, and conductive heat transfer through the metallic conductor core, which preheats unburned insulation material [4].

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Vertical cable configurations experience more rapid flame spread due to the chimney effect, with spread rates 10–30 times faster than horizontal configurations [1]. Consequences include destruction of equipment, power outages, production losses, and hazards from toxic combustion products—particularly hydrogen chloride from PVC insulation and carbon monoxide from incomplete combustion [7][8].

C. Importance of Cable Insulation

Cable insulation serves three critical functions: electrical insulation preventing current leakage and maintaining dielectric strength; thermal insulation affecting current-carrying capacity (ampacity); and mechanical protection against physical damage [9]. Key fire behaviour parameters include decomposition temperature, heat of combustion, char-forming tendency, oxygen index, smoke production, and toxicity of combustion products [1][7].

The selection of insulation materials involves complex trade-offs among electrical, thermal, mechanical, and fire performance characteristics [5][9]. While historically prioritised for electrical and thermal properties, growing awareness of fire risks has increased emphasis on fire-resistant formulations and development of new materials with improved fire performance [10][11].

D. Need for Fire-Resistant Cables

The compelling need for fire-resistant cables arises from life safety considerations, property protection requirements, and business continuity needs [1][3]. Regulatory requirements have evolved substantially, with standards such as IEC 60332 (vertical flame test), IEC 60754 (corrosivity of combustion gases), and IEC 61034 (smoke density) prescribing minimum performance levels for cables in specific applications [13].

Development strategies include halogen-free formulations eliminating toxic combustion products, flame-retardant additives modifying combustion processes, intumescent materials forming protective char layers, and fire-resistant layers providing barrier protection [12][14].

II. TYPES OF CABLE INSULATION

A. Polyvinyl Chloride (PVC)

1) Composition

PVC comprises approximately 30% of all polymeric insulation materials globally [5]. Derived from vinyl chloride monomer (CH_2=CHCl) polymerisation, commercial formulations are complex composites with the PVC resin constituting 40–60% by weight. Plasticisers (20–40%), typically phthalate esters such as DEHP, impart flexibility and processability. Stabilisers (metal soaps, organotin compounds), antioxidants, UV stabilizers, fillers (calcium carbonate, clay, silica), and flame retardants are incorporated to enhance performance and durability [5][7].

2) Advantages

PVC offers excellent electrical properties (dielectric constant 3.0–4.0, dielectric strength 10–30 kV/mm, volume resistivity 10^{12}–10^{15} Ω·cm), good mechanical properties with tailor-able flexibility, low cost from inexpensive raw materials (ethylene and chlorine), good chemical resistance, low moisture absorption, and inherent self-extinguishing tendency from halogen content [5][7].

3) Disadvantages

Critical deficiencies include production of toxic and corrosive combustion products (HCl gas forming hydrochloric acid with moisture), thermal limitations (continuous service 70–90°C, short-circuit maximum 160°C), environmental concerns from phthalate plasticizers, and challenging recyclability [7][8].

4) Fire Behaviour

PVC decomposition proceeds through two main stages: dehydrochlorination at 200–300°C, releasing 50–60% of chlorine content as HCl and forming conjugated polyene structures, followed by decomposition of polyene structures at 400–600°C, producing hydrocarbons, char (10–20% residue), and additional gaseous products [7][8].

Peak HRR values of 200–400 kW/m² at 50 kW/m² heat flux are substantially lower than polyethylene, attributed to flame inhibition by chlorine radicals scavenging flame-propagating radicals [1][8]. Smoke yields of 1,000–1,500 m²/kg represent some of the highest values among cable insulation materials, consisting of soot particles and HCl aerosols producing characteristic white smoke that severely impedes visibility [1][7].

5) Applications

Applications include low voltage building wiring, appliance cords, flexible cables, control cables (up to 1 kV), medium voltage applications (up to 33 kV), automotive wiring, and industrial power and control cables [5]. Special formulations include flame-retardant grades, low-smoke compounds for enclosed spaces, and heat-resistant grades for elevated temperature service [13].

B. Polyethylene (PE)

1) Properties

PE consists of repeating ethylene units (CH_2-CH_2)n, with three relevant types: LDPE (high-pressure free-radical polymerization, branched structure, crystallinity 45–55%, density 0.915–0.925 g/cm³, melting point 105–115°C), HDPE (coordination polymerization, linear structure, crystallinity 60–80%, density 0.940–0.960 g/cm³, melting point 125–135°C), and LLDPE (copolymerization with alpha-olefins, controlled short-chain branching) [9][10].

Outstanding electrical properties include extremely low dielectric constant (2.25–2.35), very low dissipation factor (approximately 10^{-4}), exceptionally high volume resistivity (10^{16}–10^{18} Ω·cm), and high dielectric strength (20–40 kV/mm) [9][11].

2) Advantages

Advantages include best-in-class electrical performance, excellent chemical resistance (resistant to most acids, alkalis, and salt solutions), outstanding water and moisture resistance, good mechanical properties, lightweight, favourable cost from inexpensive ethylene, and better recyclability than many alternatives [9][10].

3) Fire Hazards

Critical fire hazards include high flammability (LOI 17–18%), rapid ignition (flash-ignition 330–350°C, self-ignition 340–360°C), vigorous combustion producing hydrocarbon fragments through random chain scission, peak HRR values exceeding 1,000 kW/m² at 50 kW/m² heat flux, high heat of combustion (43–46 MJ/kg comparable to fuel oil), negligible char formation (<5% residue), substantial melt flow, and black soot smoke containing PAHs and toxic components [1][10][11].

4) Applications

Applications include low voltage and medium voltage insulation (up to 35 kV), telecommunications cables, data cables, and speciality applications requiring superior electrical performance [9][10]. Extensive research on flame retardants (halogenated, phosphorus-based, intumescent) continues to address flammability without compromising electrical properties [12][14].

C. Ethylene Propylene Rubber (EPR)

1) Rubber Insulation Properties

EPR is a copolymer of ethylene and propylene, with two types: EPM (ethylene-propylene copolymer) and EPDM (ethylene-propylene-diene monomer incorporating diene for sulfur vulcanisation) [2][6]. Compositions contain 50–70% ethylene and 30–50% propylene, providing inherent thermal stability from the saturated backbone and excellent low-temperature flexibility (glass transition typically below –50°C) [6]. Highly filled formulations contain 30–50% by weight of inorganic fillers (clay, talc, silica, alumina) and additives [2][4].

2) Thermal Resistance

Exceptional thermal stability with continuous service temperatures up to 90°C (higher for specialised formulations). Thermal degradation proceeds through thermal oxidation below 200°C (requiring antioxidant systems) and chain scission approaching 300°C [2][6]. Activation energy of 180–240 kJ/mol indicates good thermal stability, with EPR retaining mechanical properties better than PE or PVC during thermal ageing at temperatures up to 135°C [4][6].

3) Fire Resistance

Moderate fire resistance (LOI 18–22%) with peak HRR values ranging from 400–700 kW/m² at 50 kW/m² heat flux, substantially lower than PE but higher than flame-retardant PVC [1][4]. Moderate char formation (10–30%) from inorganic fillers provides a protective barrier [2][6]. Smoke production (400–800 m²/kg) is lower than PVC [1]. Aluminium trihydrate (ATH) and magnesium hydroxide fillers decompose endothermically, releasing water vapour and forming char-enhancing products (alumina, magnesia) [12][14].

4) Applications

Applications include medium voltage cables (up to 35 kV), high voltage cables (up to 138 kV and beyond), mining cables, submarine cables, offshore applications, nuclear power plants, railway traction power and control systems, motor leads, and industrial power cables for demanding environments [2][4][6].

III. FIRE BEHAVIOUR OF CABLE INSULATION

A. Ignition

Ignition involves sequential stages: heating, pyrolysis, gas-phase ignition, and flame establishment. Pyrolysis thresholds: PVC dehydrochlorination at ~200°C, PE random chain scission at ~300°C, EPR thermal oxidation and chain scission above ~250°C [1][7]. Minimum ignition temperatures: PVC 400–500°C, PE 350–400°C, EPR 350–450°C [1]. Time to ignition depends on heat flux, material properties, and geometry [14].

B. Pyrolysis

PVC pyrolysis: dehydrochlorination (200–300°C, endothermic, releasing HCl) followed by polyene decomposition (400–600°C, producing hydrocarbons, aromatics, char) [7][8]. PE pyrolysis: random chain scission producing a wide distribution of hydrocarbon fragments (alkanes, alkenes, dienes) [10][11]. EPR pyrolysis: chain scission producing hydrocarbon fragments influenced by ethylene/propylene ratio and filler content [2][6].

C. Flame Spread

Horizontal cable flame spread through convective heat transfer (primary), radiative heat transfer, and conductive heat transfer through cable core [4]. Vertical cable flame spread is 10–30 times faster due to the chimney effect [1]. PE exhibits very rapid flame spread due to high HRR and absence of char [10]. PVC exhibits slower flame spread from HCl flame inhibition [7][8]. EPR exhibits moderate flame spread influenced by filler content and char-forming tendency [2][6].

D. Heat Release

Heat release rate (HRR) is the most important fire parameter [1][14]: PVC 200–400 kW/m², PE 1,000–1,500 kW/m² (often exceeding), EPR 400–700 kW/m² at 50 kW/m² heat flux [1]. Heat of combustion: PVC 15–18 MJ/kg (reduced by chlorine content), PE 43–46 MJ/kg (highest), EPR 38–42 MJ/kg (intermediate) [1][10].

E. Smoke Production

PVC produces abundant smoke (1,000–1,500 m²/kg, white from HCl aerosols and particulate matter) [1][7]. PE produces black smoke (500–1,000 m²/kg, primarily soot particles with high optical density, containing PAHs) [10][11]. EPR produces moderate smoke (400–800 m²/kg, grey to black, influenced by filler content and combustion conditions) [1][6].

F. Char Formation

PVC forms moderate char (10–20%, porous structure, limited protection) [7][8]. PE forms negligible char (<5%, no protective barrier) [10][11]. EPR forms moderate to significant char (10–30%, influenced by filler content, more coherent structure with inorganic fillers) [2][6].

IV. VERTICAL CABLE FLAME TEST

A. Purpose

Assess flame propagation characteristics of cables under controlled vertical orientation, simulating the most critical scenario for cable safety (rapid flame propagation through chimney effect) [1][13]. Establishes acceptance criteria for cables in specific applications and identifies cables with excessive flame spread [13].

B. Standard: IEC 60332

International standard comprising Part 1 (vertical flame propagation for single insulated wire/cable), Part 2 (bunched cables), and Part 3 (cables in cable ducts). Current versions: IEC 60332-1-1 and IEC 60332-1-2 (Procedure for single insulated wire/cable) [13]. National adoptions: EN 60332-1-2 (European), BS EN 60332-1-2 (British), UL 1581 (US, similar but different procedures).

C. Test Setup

Specimen: Single cable ~600 mm length, conditioned at ambient temperature for ≥16 hours. For cables <20 mm diameter, tested individually; for >20 mm, tested as single or bundle depending on application [13].

Burner: Laboratory-scale burner with standardised flame (inner cone 20–30 mm, total flame height 100–120 mm, temperature ~960°C, propane/butane at specified pressure and flow rate) [13].

Burning Time: 60 seconds for IEC 60332-1-2 (flame application continues for full 60 seconds regardless of ignition). For bunched tests, application time varies by cable category and configuration [13].

Acceptance Criteria: Flame propagation not exceeding 50 mm from lower burner edge, self-extinguishment within specified time (typically 60 seconds). Bunched cable tests (IEC 60332-3): total propagation limited to 2.5 m (Category A) or 1.5 m (Category B) [13].

Measured Parameters: Flame propagation distance, burn duration, char length, self-extinguishing tendency, dripping behaviour, afterglow [1][13].

V. CONE CALORIMETER

A. Standard: ISO 5660

ISO 5660-1:2015 (Reaction-to-fire tests - Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method) and smoke production rate) [14]. National adoptions: EN ISO 5660-1 (European), ASTM E1354 (US, similar principle with procedural differences).

B. Principle: Oxygen Consumption Theory

Heat release is proportional to oxygen consumed (13.1 kJ per gram of oxygen) [14]. HRR is calculated from oxygen concentration in combustion gases, measured continuously by an oxygen analyser in the exhaust duct. CO and CO_2 measurements correct for incomplete combustion [1][14].

$HRR = (\Delta Hc / r0) \cdot (\dot{m}air / (1 - \varphi)) \cdot \Delta[O_2]$

where ΔHc = heat of combustion, r0 = stoichiometric oxygen-to-fuel ratio, $\dot{m}air$ = air mass flow, φ = oxygen correction factor, $\Delta[O_2]$ = oxygen depletion [14].

C. Heat Flux

Controlled radiant heat flux from electrical cone heater [14]:

- 25 kW/m²: Moderate fire exposure (early-stage or distant fires)
- 35 kW/m²: Significant fire exposure (developing fires)
- 50 kW/m²: Severe fire exposure (well-developed fires, most common for cable testing) [1]
- 75 kW/m²: Extreme fire exposure (fully developed fires)

D. Parameters Measured

1) Time to Ignition: Period from exposure start until sustained flaming (≥5 seconds) [1][14].
2) Heat Release Rate (HRR): Heat released per unit time, determining fire size and growth rate [1][14].
3) Peak HRR (PHRR): Maximum HRR value, critical for fire growth and flashover potential [1][14].
4) Total Heat Release (THR): Cumulative heat released (integral of HRR over time), representing total energy available [14].
5) Smoke Production: SPR and TSP from light obscuration measurements [1][14].
6) Mass Loss: MLR and TML from load cell, used to calculate effective heat of combustion [14].
7) CO and CO_2 Concentrations: Indicate combustion efficiency and toxic product production [1][14].
8) Residual Mass: Percentage remaining after test, indicating char-forming tendency [1][7].
9) FIGRA (Fire Growth Rate Index): PHRR divided by time to peak, providing a single measure of fire growth potential [1][14].

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VI. COMPARATIVE ANALYSIS

Table 6.1: Comparative Performance of PVC, PE, and EPR Cable Insulations

Category	Parameter	PVC	PE	EPR
Ignition & Flammability	Time to Ignition (50 kW/m²), s	30–60	40–80	35–65
	LOI, %	20–25	17–18	18–22
	Self-Ignition Temperature, °C	440–470	340–360	390–420
Heat Release	Peak HRR (50 kW/m²), kW/m²	200–400	1,000–1,500	400–700
	THR, MJ/m²	20–40	60–100	30–60
	Heat of Combustion, MJ/kg	15–18	43–46	38–42
	FIGRA, kW/m²·s	5–15	25–50	10–25
Flame Spread	Flame Spread Rate, mm/s	0.5–2	5–15	1–4
	Self-Extinguishing	Moderate	Poor	Moderate
	IEC 60332 Compliance	Pass (FR grade)	Fail	Pass (FR grade)
Smoke & Toxicity	Smoke Production, m²/kg	1,000–1,500	500–1,000	400–800
	CO Yield, kg/kg	0.05–0.15	0.10–0.25	0.08–0.20
	Primary Toxic Gases	HCl, CO, C_2H_2	CO, PAHs	CO
	Smoke Color	White (acidic)	Black (soot)	Gray
Char Formation	Char Yield, %	10–20	<5	10–30
	Protective Barrier	Moderate	Negligible	Moderate
Thermal Properties	Service Temperature, °C	70–90	70–90	90–105
	Peak Temperature, °C	105–120	80–100	130–150
Environmental Impact	Halogen Content	High	None	None
	Corrosive Gas	High (HCl)	Low	Low
	Disposal Challenges	High	Moderate	Moderate

Sources for Table 6.1: Data compiled from [1][2][4][5][6][7][8][9][10][11][13]

Key Observations Summary

Performance Aspect	Best Performer	Worst Performer	Rationale
Fire Resistance	PVC	PE	PVC releases HCl, which inhibits flame; PE has high hydrocarbon content [1][7][10].
Smoke Production	EPR	PVC	EPR produces the least smoke; PVC produces HCl aerosols [1][6][7].
Heat Release	PVC	PE	PVC has the lowest heat of combustion (15–18 MJ/kg) [1][7][10].
Thermal Stability	EPR	PVC	EPR withstands up to 150°C; PVC degrades above 120°C [2][6][7][8].
Environmental Safety	PE / EPR	PVC	PVC releases HCl and phthalates; PE/EPR are halogen-free [5][6][7][9][10].
Flame Spread	PVC	PE	PVC has a slow spread rate and forms a protective char; PE does not char [1][7][10].

Sources for Key Observations Summary: Data compiled from [1][2][5][6][7][8][9][10]

VII. DISCUSSION

A. *Explanation of PVC Fire Behaviour*

PVC fire behaviour is dominated by chlorine in the polymer structure [7][8]. The dehydrochlorination reaction is endothermic, absorbing heat and reducing energy available for flame propagation (20–30% HRR reduction compared to hydrocarbon polymers) [1][7]. HCl released acts as a flame retardant by reacting with flame-propagating radicals (H•, OH•), inhibiting gas-phase chain reactions and diluting flammable gases [1][8].

Char formation (10–20%) provides a protective barrier limiting oxygen access and reducing heat transfer [1][7]. However, char structure is porous, providing only moderate protection [7]. High smoke production (1,000–1,500 m^2/kg) consists primarily of HCl aerosols and particulate matter, which are corrosive and toxic [1][7]. The white smoke from PVC can be visually deceptive but is more hazardous than black soot due to HCl content [7][8].

Environmental impact is dominated by HCl production, causing acid rain effects, phthalate plasticizer leaching, and challenging disposal due to potential HCl release [5][7].

B. Explanation of PE Fire Behaviour

PE fire behaviour is determined by high hydrocarbon content and lack of flame-retardant elements [9][10]. Thermal decomposition produces a wide range of flammable hydrocarbons supporting vigorous combustion, with a very high heat of combustion (43–46 MJ/kg) resulting in intense heat release [1][10].Absence of halogen atoms means no gas-phase flame inhibition [10][11]. Hydrocarbon fragments are highly reactive and support rapid flame propagation [1][10]. No char formation means no protective barrier [10]. Molten PE can flow and spread fire to other areas [1].

High HRR exceeding 1,000 kW/m^2 at 50 kW/m^2 heat flux indicates potential for rapid fire growth and flashover conditions [1][10]. Black soot production contains PAHs and toxic compounds with high optical density, severely reducing visibility [10][11].

Environmental impact primarily through CO production (systemic toxicant) and soot emissions, though absence of halogenated compounds reduces corrosive potential [9][10]. Extensive research on flame retardants continues to develop effective halogen-free solutions [12][14].

C. Explanation of EPR Fire Behavior

EPR fire behaviour is influenced by polymer structure, filler content, and formulation [2][6]. A saturated backbone provides inherent thermal stability with decomposition at higher temperatures than PE [6]. Filler content reduces HRR and provides char-forming components [2][4]. Decomposition through chain scission produces hydrocarbon fragments similar to PE but with different distribution [2][6]. Methyl groups from propylene units affect pyrolysis product distribution [6]. Lower hydrocarbon density than PE reduces flammability [1][2].

Filler content is critical: inorganic fillers (clay, talc, alumina) act as heat sinks, reduce HRR, and contribute to char formation, providing a protective barrier [2][4][6]. Aluminium trihydrate and magnesium hydroxide release water vapor diluting flammable gases [12][14].

Smoke production is influenced by filler content and combustion conditions: relatively low under well-ventilated conditions, substantial under underventilated conditions [1][6]. Environmental impact lower than PVC (no halogenated compounds) but comparable to PE, with filler content potentially introducing concerns if containing heavy metals [6].

D. Implications for Cable Selection

PVC: Suitable for cost-sensitive applications where fire performance is acceptable; self-extinguishing tendency and moderate HRR provide adequate fire resistance; limited by high smoke production and HCl release in safety-critical and enclosed spaces [1][5][7].

PE: Suitable for applications where electrical performance is paramount, and fire hazards are mitigated; outstanding electrical properties unmatched by other materials; high
flammability and absence of char formation require careful fire protection measures [1][9][10].

EPR: Suitable for demanding applications requiring fire performance, thermal stability, and flexibility; intermediate fire performance and high thermal resistance make EPR ideal for high-temperature and fire-risk applications; filled formulations provide improved fire resistance at the cost of increased density and reduced flexibility [1][2][6].

VIII. FUTURE SCOPE

A. AI Prediction of Cable Fire

AI and machine learning enable early warning systems through continuous monitoring and early detection of fire precursors [12][14]. AI algorithms analyse gas sensor data, temperature monitors, and electrical parameters to identify patterns preceding cable fires [3][5]. Neural networks provide real-time fire risk assessment based on operational conditions [12]. Integration with gas sensing technology enables distinguishing between overheating and discharge conditions by analysing concentrations and ratios of characteristic gases [3][5]. Requires large datasets of cable behaviour under various conditions, with experimental testing providing training data and IoT technologies enabling continuous monitoring [14].

B. Nano-Additives for Fire Retardancy

Nanomaterials provide flame retardancy at low loading levels, minimising impact on electrical and mechanical properties [12]. Carbon-based nanomaterials (carbon nanotubes, graphene) form protective char layers and promote heat dissipation, reducing PHRR by 30–50% in PE and EPR at 0.5–3 wt% addition [12]. Metal oxide nanoparticles (TiO_2, ZnO, Al_2O_3, MgO) enhance fire resistance through thermal stabilisation and char formation [12][14]. Nano-clays (montmorillonite) provide barrier properties, reducing heat and mass transfer [12]. Requires careful optimisation of additive type, loading, and surface modification [14].

C. Graphene Insulation

Graphene and graphene-based materials offer exceptional properties: high thermal conductivity, high electrical conductivity, and excellent mechanical properties [12]. Graphene oxide (GO) and reduced graphene oxide (rGO) as fillers provide barrier properties inhibiting gas and vapour permeation, with improved thermal conductivity enabling higher current-carrying capacity [12]. Enhanced mechanical properties improve stress resistance [9][12]. Reduced flammability and smoke production improve fire safety [12][14]. Graphene-based coatings can be applied to conventional cables for enhanced fire resistance without replacing insulation [12].

D. Hybrid Flame Retardants

Hybrid flame retardants combining multiple mechanisms provide synergistic effects at lower loading levels [12][14]. Metal hydroxide fillers (ATH, MDH) combined with phosphorus compounds provide endothermic cooling, dilution effects, char formation, and gas-phase inhibition, achieving V-0 rating at lower loading than individual components [12]. Intumescent flame retardants combined with nanoparticles reinforce char structure and improve barrier properties, providing self-extinguishing behaviour and low smoke production [12][14]. Surface functionalization improves compatibility with the polymer matrix and enhances dispersion [12].

E. Eco-Friendly Cable Insulation

Halogen-free materials with reduced environmental impact and improved recyclability [12][14]. Bio-based polymers from renewable sources (PLA, PHA) offer potential for cable insulation [9][12]. Recyclable thermoplastics replacing thermosetting materials enable reprocessing at end of life [10][12]. Halogen-free formulations (phosphorus-based, intumescent flame retardants) improve environmental and health characteristics [12][14]. Requires a holistic approach considering environmental impact throughout the lifecycle, with life cycle assessment as an important evaluation tool [14].

F. Machine Learning Prediction

ML algorithms predict cable fire behaviour and optimise insulation formulations by identifying patterns in complex datasets [12][14]. ML models predict ignition characteristics, HRR, and smoke production from material composition and test conditions, accelerating development of new formulations [12]. Feature selection identifies important parameters informing material design [14]. Deep learning approaches (neural networks, deep regression models) capture nonlinear relationships and interactions, trained on large datasets from experiments and simulations [12].

IX. CONCLUSION

This comprehensive review examined the comparative fire behaviour, operational integrity, and environmental impact of the three principal polymeric cable insulation materials: polyvinyl chloride (PVC), polyethylene (PE), and ethylene propylene rubber (EPR) [1][2][5][6][7][9][10].

PVC exhibits moderate fire performance with inherent flame retardancy from chlorine content [1][7][8]. The dehydrochlorination reaction absorbs heat and produces HCl, inhibiting gas-phase combustion, providing the lowest heat release rate (200–400 kW/m² peak HRR) and best intrinsic fire resistance [1][7][8]. However, this comes at the cost of high smoke production (1,000–1,500 m²/kg) and toxic HCl emissions [1][7]. Environmental impact is substantial from corrosive acid gases and phthalate plasticizers [5][7]. Continuous service temperature limited to 70–90°C [5][7].

PE provides outstanding electrical properties with the lowest dielectric constant and loss factor, ideal for high-frequency and high-voltage applications [1][9][10]. However, fire behaviour is the poorest, with the highest heat release rate (1,000–1,500 kW/m² peak HRR), most rapid flame spread, and negligible char formation [1][10]. High heat of combustion (43–46 MJ/kg) and absence of inherent flame retardancy create significant fire hazards [1][10][11]. Black soot smoke with high optical density and substantial CO emissions are significant concerns [10][11]. Service temperature limited to 70–90°C [9][10].

EPR provides the best thermal stability (continuous service 90–105°C, peak 130–150°C) and intermediate fire performance (peak HRR 400–700 kW/m² at 50 kW/m² heat flux) [1][2][4][6]. Filler content contributes to moderate char formation (10–30%), providing barrier protection [2][6]. Smoke production (400–800 m²/kg) is lower than PVC but comparable to PE [1][6]. Environmental impact is moderate with no halogen emissions [6]. Excellent flexibility and mechanical properties make EPR suitable for demanding applications [2][4][6].

A. Key Comparative Findings

1) Best Fire Resistance: PVC (due to HCl flame inhibition) [1][7][8]
2) Best Electrical Properties: PE (lowest dielectric constant and loss) [1][9][10]
3) Best Thermal Stability: EPR (highest service temperature) [1][2][6]
4) Highest Smoke Production: PVC (1,000–1,500 m²/kg) [1][7]
5) Highest Heat Release: PE (1,000–1,500 kW/m² peak HRR) [1][10]
6) Highest Environmental Impact: PVC (HCl emissions, phthalates) [5][7]
7) Best Overall Balance: EPR (moderate across all parameters) [1][2][6]

B. Test Methods

1) Vertical cable flame test (IEC 60332) provides direct assessment of flame propagation and self-extinguishing [1][13]
2) Cone calorimeter (ISO 5660) provides detailed data on HRR, smoke production, and char formation [1][14]

C. Future Developments

1) AI prediction and machine learning for early warning and fire prediction [12][14]
2) Nano-additives and hybrid flame retardants for enhanced fire performance [1][12][14]
3) Eco-friendly materials reducing environmental impact [12][14]
4) Graphene-based insulation and coatings [12]

X. CONCLUSION

The selection of cable insulation material requires careful consideration of application requirements, fire safety needs, and environmental constraints [1][5][6][9]. PVC provides cost-effective fire resistance with trade-offs of high smoke and toxic gas production [1][5][7]. PE provides superior electrical performance with trade-offs of high flammability [1][9][10]. EPR provides balanced performance with best thermal stability and good fire resistance [1][2][6]. Optimal selection depends on the relative importance of fire performance, electrical properties, thermal stability, and environmental impact for each application [1][5][6][9][10].

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