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# Recyclable Polymeric Cable Insulation Materials: A Comprehensive Review

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## Abstract

Global consumption of electrical cables continues to grow with increasing electrification and infrastructure projects. Cross-Linked Polyethylene (XLPE) has been used as a traditional non-recyclable insulating material for cable insulation for many years due to its good dielectric, mechanical, and thermal properties and economic viability. The volume of waste generated increases daily due to XLPE, which contributes to growing landfill sites. Recyclable insulation of electric cables is significant in promoting environmental sustainability and resource efficiency, akin to substantial advantages over XLPE. Additionally, recyclable materials help conserve non-renewable petroleum resources. This review article presents an overview of recyclable polymeric insulation materials that can be an alternative solution to XLPE. Recyclable polymeric materials like Polypropylene (PP), Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and polyolefins are briefly discussed in this paper. PP and its blend composites and test results of electrical and mechanical properties are further explained.

**Keywords:** HDPE, LDPE, PP, Polymeric Insulator, Recyclable Cable Insulation, Recyclable Polymers, XLPE

## 1. Introduction

Power cables play a crucial role in power systems. In the current era, the need for electricity is increasing with the rapid development of urban areas. So, the demand for power cables is also expanding as power cables are the backbone of power transmission and distribution[1]. Earlier, paper insulation was widely used for insulating conductors. The first infused paper-insulated lead-sheathed cable was formed by John Barrett of AT&T in the U.S.A., and it was a telephone cable. Paper-Insulated Lead Cables (PILC) were made in the 19th century with various paper of manila-rope fibres. Paper insulation is not used that much as it has many drawbacks. Moreover, material science is evolving daily with advanced materials and properties[2].

Crosslinked Polyethylene (XLPE) is widely used nowadays instead of paper insulation. Polyethylene (PE) is a good choice as it is an excellent dielectric material that is cheap and easy to process. To ensure the end-use requirement, it must withstand the service temperature up to 90°C[3]. It is crosslinked mostly with peroxide to enhance PE's property and service temperature. XLPE possesses significant properties after crosslinking such as high operation temperature, less dielectric loss, and improved resistance to chemicals and oils. However, XLPE has some disadvantages as an insulation material, including undesirable space charge accumulation, a lengthy processing time, and non-recyclability[4].

Scientists are now looking for a sustainable material to reduce their carbon footprint, as XLPE is a thermoset polymer affecting our environment. Once the cables are damaged or discarded, they will be disposed of in a landfill and do not degrade quickly. Recyclable insulation materials can mitigate this issue by offering avenues for repurposing and reusing materials and reducing landfill sites. Generally, thermoplastic polymers are recyclable and can be processed again. At present, scientists are moving towards thermoplastic polymers like PP, LDPE, and HDPE. Some polymers are getting attention due to their recyclability, easy processing, availability, and inexpensive material[5].

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In this paper, we will briefly discuss the recyclable insulation materials, blends of PP, and composites for cable insulation systems that scientists have explored over some time for an alternative option.

# 2. Polymers

Polymers are macromolecules composed of repeating small units called monomers. The word 'Polymer' was taken from Greek, where 'Poly' means many and 'mer' means unit. It poses long chains and high molecular weight. The process by which monomers are connected to form a long polymer chain is called polymerization[6].

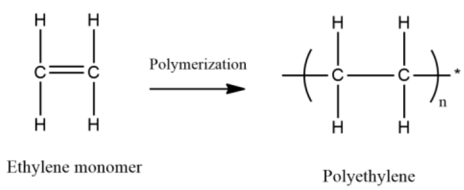


**Figure 1.** Structure of polyethylene from ethylene monomer.

E.g., Polyethylene is a polymer made up of ethylene monomer (repeating unit) by polymerization process. The structure is depicted in Figure 1.

There are different types of polymers under various categories. In Figure 2, a flow chart is shown.

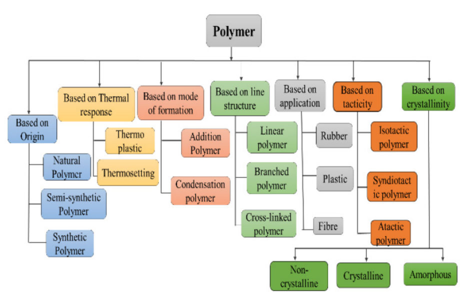


**Figure 2.** Flow diagram of different types of polymers.

## 2.1 Advantages of Polymers as an Electric Insulator

Polymers have a lot more advantages as electric insulators than conventional insulating materials. Some of the advantages include[7]:

### *2.1.1 Lightweight*

The density of conventional insulation materials is much higher than polymers. The difference in the weight is increased with the voltage class rating. The polymeric materials weigh much less than the other insulating materials, so they do not require cranes or lifting devices to install, and the handling cost is much less. A new compact transmission line can be designed with a polymer insulator, which is less expensive than porcelain insulators.

### *2.1.2 Ease of Processing*

Generally, polymer insulating housings are molded, a cost-effective process for designing parts. A complex profile can be made without yield problems or production problems. The process of manufacturing polymers usually takes a shorter duration than the other types of insulating materials. The processing time for the final product is less than for other materials, as molding is done very quickly.

### *2.1.3 Lower Pollution Impact due to Less Surface Energy*

Polymeric materials have low surface-free energy and are primarily used in outdoor insulation. Polymeric materials restrict surface wetting due to their hydrophobic nature, which is when they are unexposed to the environment and new in the field. However, retaining hydrophobic properties when exposed to the environment is very difficult. Generally, water beads are formed on the surface of the hydrophobic materials, which dissolve the contamination within the beads and restrict the leakage of electric current flow. This contamination increases the conductive nature, but water beads help to retain the insulating property of hydrophobic materials by dissolving contamination. This results in keeping much better resistance to flashover of polymers.

### *2.1.4 Dielectric Property of Polymer*

Electrical properties like the dielectric property of a material can easily break at a micron or nanoscale point. Natural materials with dielectric properties have some limitations that affect the breakdown strength. Polymers have suitable dielectric properties that increase breakdown strength. Many factors affect the dielectric properties of polymers[8]. The dielectric property measures electric charge movement when an external electric field is applied.

## 2.2 Challenges of Polymers as an Insulator

Polymers have many advantages as an insulator but have some drawbacks that need to be improved.

### *2.2.1 Sustainability of Polymers under High Service Temperature*

Because of the increased electricity demand, High Voltage Direct Current (HVDC) is used significantly with a large electric current carrying capacity. This large carrying capacity leads to high service temperature. Maintaining electrical properties under high service temperatures is an issue, and polymers like XLPE, PE, and PP cannot withstand the temperature, so the insulating property also gradually decreases[9].

### *2.2.2 Degradation Nature of Polymers*

Polymeric insulators face some aging problems after a certain period of service life. Various factors accelerate the degradation of polymers. It includes biological factors, chemical factors, UV light, environmental stress, etc. These factors break the polymeric chain, which leads to degradation. Ultimately, it affects the outdoor insulation property. The specific cable insulator design can improve the polymeric materials' aging problem[10].

### *2.2.3 Problem in Electrical Tracking and Erosion*

Generally, when polymeric insulators are exposed to the environment, they start losing their hydrophobic property due to continuous surface wetting. It makes the insulator more vulnerable to the dry band arcing-induced tracking erosion. Electrical tracking is defined as making a conductive path on the insulator's surface, meaning loss of dielectric property. This happens because of contaminants like dust, dirt, acid rain, or some conductive particles in the environment[11].

## 2.3 Challenges of Existing Polymeric Insulation Materials

XLPE is the most widely used extruded insulator for cable application. It has outstanding properties like electrical, thermal, and mechanical properties and is a cost-effective material. Polyethylene, XLPE is made, and dicumyl peroxide is used as a crosslinking agent. XLPE shows an operating temperature that is improved more than polyethylene, from 70°C to 90 °C. However, the problem with XLPE is that it is a thermoset polymer that cannot be recycled as it has cross-link networks and forms strong covalent bonds between chains, which are very difficult to break, so they go directly to landfills. Different types of recycling methods are now introduced, depicted in Figure 3, but the cost of processing is high, and handling is also a bit challenging[12]. Researchers are now trying to use recyclable polymers to overcome the sustainability problem.

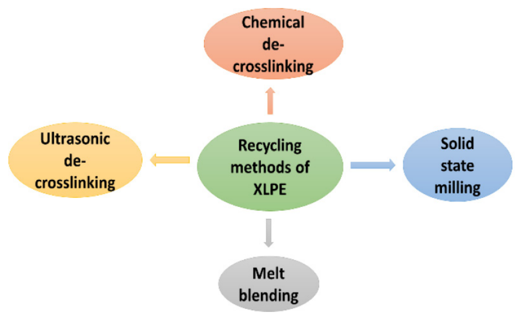


**Figure 3.** Flow diagram of different types of recycling process[12].

Thermoplastic polymers are now a primary research focus as they are recyclable due to the weak bond between polymer chains. Over the years, PP has gained popularity as an alternative option to XLPE, a thermoplastic polymer. PP's melting point and working temperature are 160°C and 100-120°C, which is more than polyethylene, and electrical properties are also reasonable compared to XLPE[13].

## 2.4 Recyclable Polymeric Materials

Thermoplastic polymers are eco-friendly as they can be recycled, reducing carbon emissions and environmental pollution. PP, LDPE, and HDPE are now trying to replace XLPE as these materials are not costly and have the required properties, and some composite materials of these polymers are also used.

### *2.4.1 PP*

In the last few years, PP-based cable insulators have been developing to meet the requirements and replace the traditional crosslinked polymers. The structure of PP is illustrated in Figure 4.

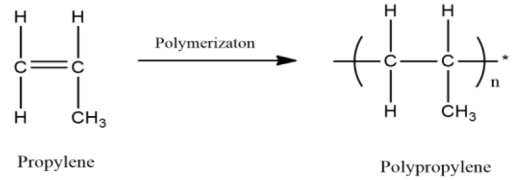


**Figure 4.** Structure of polypropylene.

As the HVDC cable system grows rapidly, the need for materials with high operating temperatures also increases. PP has various advantages over XLPE; it has good mechanical and superior thermal properties, increasing interest in industrial applications and the academic section. PP has a melting point of 170°C allows it to withstand higher service temperatures. Humidity has a low impact on the insulation property of PP because of its hydrophobic nature. PP has good electrical properties, which include low dielectric constant, high breakdown strength, low dielectric permittivity, and high DC volume resistivity[14]. PP is a cheap, recyclable polymer material. PP can be used without crosslinking and byproducts.

### 2.4.2 Low-Density Polyethylene (LDPE)

Low-density polyethylene is formed by ethylene monomer. LDPE is a thermoplastic polymer that can recycle and reuse material, making it eco-friendly. This material is widely used in high-voltage insulating systems. Virgin LDPE has characteristics including flexibility, good mechanical strength, high impact strength, and good fatigue life. However, LDPE has some drawbacks, such as its melting temperature being lower than PP's, which restricts it from high-voltage applications. Figure 5(a) shows the structure of LDPE.


**Figure 5.** Structure of (a) LDPE (b) HDPE.

LDPE cannot withstand high service temperature and high pressure[15]. Nanofillers are used to improve the properties of virgin LDPE, such as dielectric properties and thermal properties. Different kinds of metal oxides like ZnO, MgO, and $TiO_2$ are used as nanodielectric materials to improve the dielectric properties of LDPE. It has been seen that the incorporation of nanofillers improves space charge accumulation[16].

### 2.4.3 High-Density Polyethylene (HDPE)

High-density polyethylene is a thermoplastic polymer that forms by attaching repeating ethylene units. HDPE has a higher degree of crystallinity[17]. HDPE can also be recycled, but due to its brittle nature, its mechanical properties need to be improved. Ramkumar *et al.*[17] did an experiment where they saw that adding alumina ($Al_2O_3$) nanofillers enhanced the properties of HDPE. It improves the dielectric property of HDPE, thermal conductivity, and breakdown voltage. Figure 5(b) depicts the HDPE structure.

### 2.4.4 Polyolefins

Polyolefins are a class of exciting materials. They contain many unique materials like polyethylene, polypropylene, and other materials[18]. This polymer is generally derived from a small group of simple olefins (alkenes). The structure of polyolefin is illustrated in Figure 6.

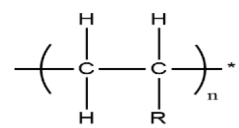

**Figure 6.** The general structure of polyolefin.

Polyolefins are used as insulation material as they have many advantages, including good electrical properties like excellent dielectric strength, low dielectric constant, good resistance to moisture, high resistance to chemicals and solvents, etc[19].

## 3. PP, Its Blends and Composite: An Alternative Approach towards Recyclable Cable

Polypropylene (PP) is a suitable material for the application of high-voltage power cable insulation systems over other polymeric materials. PP shows good properties required for insulation among different types of polymers like high-temperature tolerance, solvent resistance, corrosion resistance, and cost-effective polymer. Adding nano dielectrics like metal oxide fillers such as $Al_2O_3$, ZnO, MgO, $TiO_2$, etc., has improved electrical, mechanical, and insulation properties. Some of the research now on PP focusing on recyclable cable insulators is discussed.

### 3.1 Styrene Grafted PP

Modification of PP with the grafting technique has been proven to enhance its electrical properties. Yuan *et al.*[20] did research where they grafted styrene onto PP. In this study, the researcher chose i-PP (Isotactic PP) as a polymer matrix and different percentages of styrene were used for grafting. The grafting process is done using the water phase suspension technique. It has been seen that thermal properties, electrical properties, and crystalline structure have improved than the virgin PP. The thermal property was investigated through the DSC curve, where the melting and crystallization points show an improvement in the styrene-grafted PP over the virgin PP. As styrene is a bulky group, it has restricted the movement of PP, which enhances the crystallization property and improves melting temperature. Electrical properties like DC volume resistivity, space charge accumulation, and DC breakdown strength were also enhanced. In Figure 7, it is shown that the styrene-grafted PP shows higher volume resistivity, which indicates less leakage of current, i.e., low mobility to carry charge. However, increasing the grafting percentage may deteriorate the electrical properties of PP.

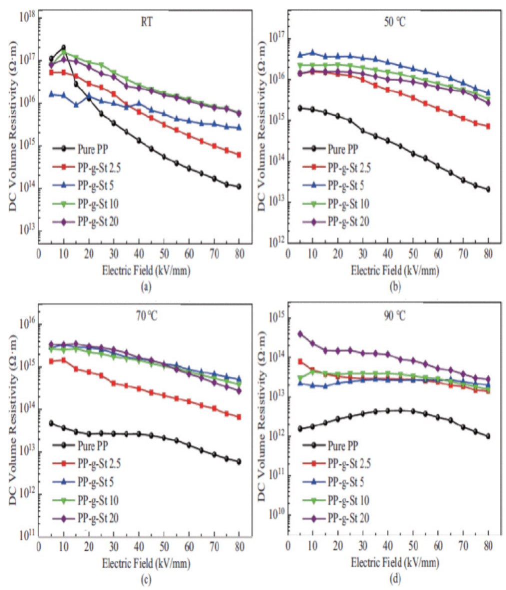


**Figure 7.** DC volume resistivity of virgin PP and styrene grafted PP under DC electric field at temperature. **(a)** 30°C, **(b)** 50°C, **(c)** 70°C, **(d)** 90°C[20].

Huang *et al.*[21] have also worked on styrene-grafted PP, finding that the blend shows significantly improved electrical and mechanical properties. In Table 1, researchers compare different grafted PP with XLPE. The result shows that elongation at break and tension modulus have greatly improved. The chain became more extended because the crosslinking network structure was not formed in grafted PP. Additionally, the intermolecular bonding force was reduced due to the large amount of styrene group, which led to a slippage of molecular chains; thus, the elongation at the break of grafted PP has slightly improved than XLPE.

**Table 1.** Comparison of mechanical properties of grafted PP with XLPE[21]

| Mechanical Properties | XLPE | Grafted PP |
|---|---|---|
| Tension Modulus (MPPa) | 120.9 ± 7.4 | 538.3 ± 45.5 |
| Elongation (%) | 555.6 ± 19.7 | 652.7 ± 32.3 |
| Tensile strength (N/mm$^2$) | 28.8 ± 7.1 | 31.8 ± 2.1 |

DC breakdown strength was also evaluated, which shows improvement in grafted PP over XLPE. Figure 8 depicts the DC breakdown plot. The enhancement in breakdown strength of grafted PP is because of the groups of styrene, which have introduced large traps that hold the charge carriers in the break breakdown process. This reduced kinetic energy and movement of energy exchange, increasing DC breakdown strength. Moreover, grafted PP can be an alternative solution to XLPE as it shows promising advantages.

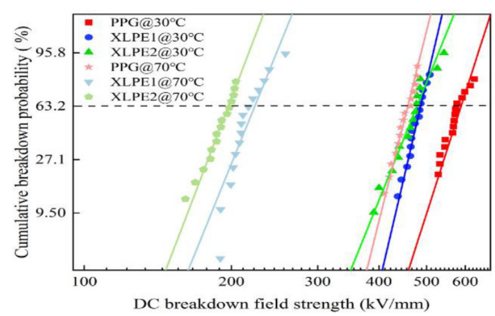


**Figure 8.** Weibull distribution of DC breakdown field strength[21].

## 3.2 Block PP and Styrene-Ethylene-Butylene-Styrene (SEBS) Tri-Block Copolymer Blend

As PP is a suitable candidate for environment-friendly cable insulation material, the researcher has blended PP with different polymers to enhance the properties as required. Liang *et al.*[22] have found that a blend of block PP with SEBS has enhanced thermal, mechanical, and electrical properties. A simple melt-blending process is followed to blend two polymers. In this blend, the researcher found that the mechanical properties improved with increasing SEBS. Table 2 clearly shows that SEBS softens the block PP, and toughness is also enhanced as the elongation at break increases with the increasing amount of SEBS. Thermal stability and break breakdown strength have also increased with the rise of blending, and space charge accumulation has decreased significantly.

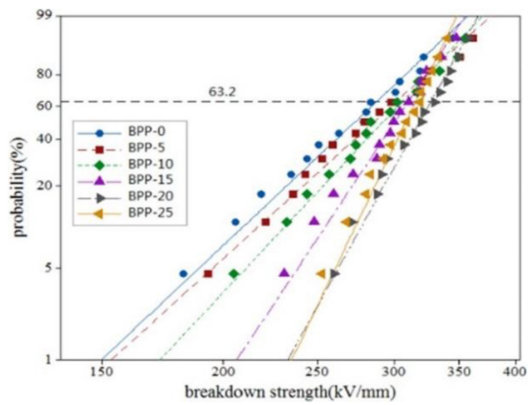


**Figure 9.** Weibull distribution of the DC breakdown strength of block PP/SEBS[22].

DC breakdown strength has been evaluated, and it was found that the breakdown strength increased from 287.8 kV/mm to 327.5 kV/mm by the addition of SEBS content from 0 wt% to 20 wt%. Figure 9 shows the DC breakdown strength plot. SEBS poses resonance structure, which is vital in improving breakdown strength. The possible theory behind this is that delocalized π-electrons present in the benzene rings have absorbed and dissipated the high energy of the excited electrons and relatively produce firm cation and anion radicles in the process of transport. Hence, it reduces the possibility of high-energy electrons attacking the chains of polymer. This blend will help to develop eco-friendly cable insulation.

**Table 2.** Mechanical properties of Block PP and SEBS[22]

| Desig nation | Tensile strength (MPa) | Elongation At break (%) | Elastic modulus (MPa) |
|---|---|---|---|
| BPP (0) | 24.70 | 537.10 | 906.50 |
| BPP (5) | 24.80 | 559.70 | 820.30 |
| BPP (10) | 25.00 | 661.80 | 773.70 |
| BPP (15) | 28.30 | 838.30 | 651.90 |
| BPP (20) | 33.60 | 1024.20 | 601.70 |
| BPP (25) | 37.20 | 1109.10 | 539.30 |

Thermoplastic elastomers can improve the toughness by blending with PP. However, it has been seen that an excessive quantity of blending thermoplastic elastomer can decrease the electrical insulation property of PP. In another study, Zhang *et al.*[23] found that acetylated SEBS blend with PP has improved mechanical and mechanical properties.

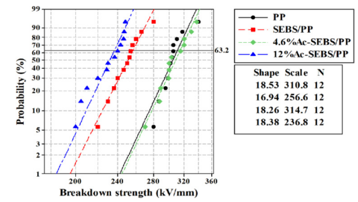


**Figure 10.** DC breakdown strength of PP/acetylated SEBS blend[23].

In Figure 10, the DC breakdown plot shows that the SEBS/PP blend shows lower breakdown strength than the acetylated SEBS blend with PP. This is due to polar groups in SEBS, which leads to deep traps in the material. These traps reduce the conductivity by trapping the charges. These traps also inhibit space charge accumulation to some extent.

## 3.3 Composite of PP with $Al_2O_3$

PP is the central area of focus because of its recyclability, good electrical properties, and service temperature. To replace traditional XLPE, it needs to meet specific requirements for cable insulation. Zhou *et al.*[24] have found an alternative solution to replace XLPE. They have developed a composite of PP and $Al_2O_3$ as a recyclable material. $Al_2O_3$ nanoparticles have been introduced specifically to enhance the electrical properties of PP. PP is melt blended with $Al_2O_3$ in a mixer. Then, compression molding is done to get film samples with different thicknesses. Researchers have found that 3 phr is enough to get the required properties. From this composite, they have seen that the accumulation of space charge has reduced, and breakdown strength and volume resistivity have also improved. Figure 11 shows the DC breakdown strength of the composite, where it was observed that the DC breakdown strength was increased by increasing the nanoparticle content by up to 3 phr. Further increase in nanoparticle content decreases the breakdown strength. The addition of nanoparticles concealed the accumulation of space charge due to increased traps.

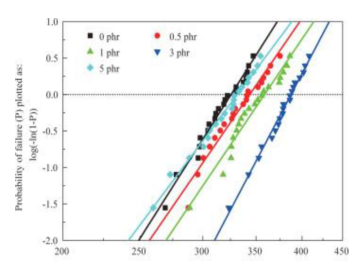


**Figure 11.** Weibull plots of DC breakdown voltage of PP/$Al_2O_3$[24].

Zhang *et al.*[25] have worked with block PP and $Al_2O_3$. Simple melt blending process they followed. They observed that the electrical properties have significantly improved. Nanoparticles were well dispersed in a polymer matrix, which increased the trap density. 1 wt% of $Al_2O_3$ improved the DC breakdown strength, and the accumulation of space charge was also suppressed at high temperatures. The study on PP along with $Al_2O_3$ is limited, and further research can be done to determine more aspects of recyclable cable insulation.

## 3.4 Composite of PP with MgO Nanoparticles

Nanodielectrics have proven to enhance the properties of polymers. Several research studies indicate that incorporating nanoparticles improves a polymer's mechanical, thermal, and electrical properties. Zha *et al.*[26] have worked on PP, where they incorporated MgO but with modification and blended SEBS to enhance the dispersibility of nanofiller. 3D flower-like structural MgO was synthesized and incorporated. In this composite researcher found that the thermal, electrical, and mechanical properties were notably improved. It was observed that 0.5phr filler content loading increased the tensile strength as well as elongation at break percentage. The mechanical properties were enhanced due to the better interfacial adhesion between polymer chains and fillers. However, adding more fillers decreased the mechanical properties as stress accumulated in the filler particles. In Figure 12, the stress-strain curve and elongation at break are illustrated.

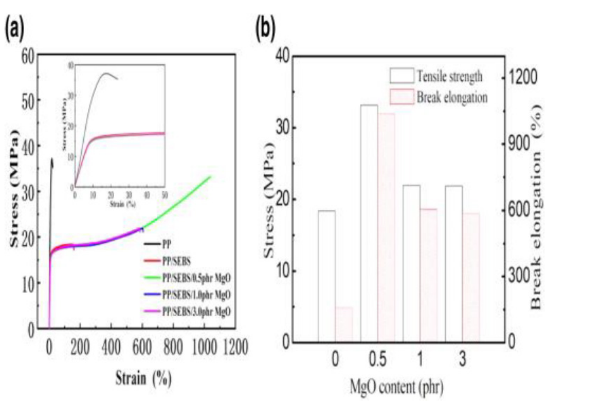


**Figure 12.** Mechanical properties of PP/SEBS/Flower MgO composite **(a)** stress-strain curve, **(b)** histogram of tensile strength and elongation at break[26].

In Figure 13, DC breakdown strength is illustrated, showing that 0.5phr filler content has improved breakdown strength. This improvement is due to increased traps with the inclusion of MgO. These large traps hold the charge carriers. The polymeric chains along with the surface gap in fillers are bonded well, which creates a charge adsorption point, and the migration of charges is inhibited; thus, the breakdown strength is improved. However, the loading of excessive fillers decreased the breakdown strength due to the increase in space charge.

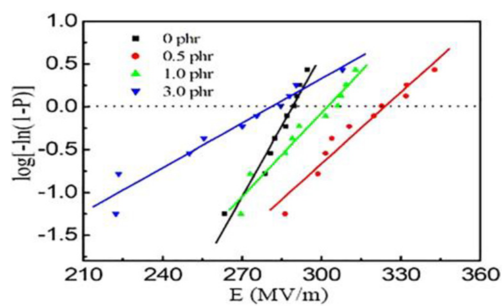


**Figure 13.** Weibull distribution plot of breakdown strength of PP/SEBS/Flower MgO composite[26].

Hu *et al.*[27] investigated the properties of PP composite to replace the XLPE, where MgO nanoparticles were incorporated with surface modification. The surface of MgO nanoparticles was modified by four types of silane coupling agents with a chain of alkyl groups to improve the dispersibility of the nanoparticles within the polymer matrix. Coupling agents are methyltrimethoxy-silane (C1), propyltrimethoxysilane (C8), octyltrimethoxysilane (C8), octadecyl-trimethoxysilane (C18). It was observed that PP composite's mechanical properties were better than pure PP's.

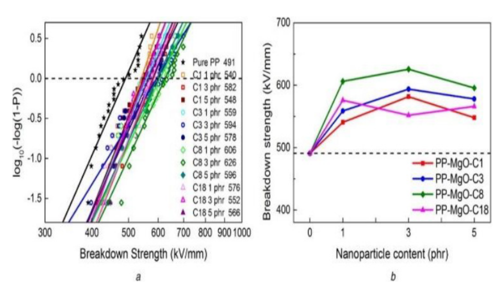


**Figure 14.** DC breakdown strength of modified MgO composites[27].

Figure 14 shows the DC breakdown strength of the composite. The breakdown strength of PP-MgO-C8 was higher than that of other composites with a content of 3 phr.

The rise in breakdown strength is due to the incorporation of surface-modified MgO nanoparticles, which induce traps within the composite. With the increasing amount of alkyl group chain length of the coupling agents, the density of the traps also increases. These abundant traps can catch the carriers of charge, which restricts the mobility of charge carriers and improves the potential barrier. This kind of composite can be an alternative option to XLPE with the advantage of recyclability of the material.

### 3.5 PP with Nano Silica ($SiO_2$) Composite

PP is a promising material for the application of cable. But pure PP has some restrictions like space charge accumulation, limiting their cable application. Chi *et al.*[28] have researched a composite of PP/POE blend with nano $SiO_2$ and observed that dielectric and mechanical properties have improved. It was seen that the dispersion of POE in the polymer matrix showed the toughness of PP. The incorporation of nano $SiO_2$ suppresses the space charge and enhances the breakdown strength of PP.

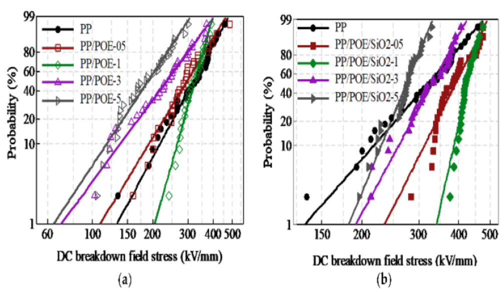


**Figure 15.** Weibull distribution of breakdown strength (a) blend of PP with POE, (b) blend of PP and POE with nano $SiO_2$[28].

In Figure 15, DC breakdown strength is analyzed, and it is found that the breakdown strength was improved by adding 10 phr POE and 1 phr of $SiO_2$. However, increasing POE and $SiO_2$ content reduces the breakdown voltage. This is due to the extensive distribution of POE in the PP polymer matrix, which creates weak areas of concentrated electric field. So, the electrons can move freely, leading to the breakdown of PP/POE. In one more study, Gao *et al.*[29] used SEBS as a toughening filler with nano silica by the melt blending process. This composite did not change thermal properties by adding SEBS and nano $SiO_2$. The breakdown strength of XLPE, PP, and its composites were evaluated and plotted using the Weibull distribution method. At room temperature, XLPE showed the highest breakdown strength, but at 70°C and 90°C, breakdown strength had decreased to 290 kV/mm and 230 kV/mm. On the other hand, the addition of SEBS into PP has decreased the breakdown strength at room temperature. This is due to the lower breakdown strength of SEBS, and SEBS decreased the crystal regularity of PP. However, the addition of nano $SiO_2$ particles in PP has significantly increased breakdown strength as nanoparticles introduced deep traps, which reduced the mobility of charges. SEBS/PP/$SiO_2$ did not show better breakdown strength than PP/SEBS/$SiO_2$. This is due to the lower dispersion of nanoparticles in SEBS than in PP. The breakdown strength graph is depicted in Figure 16.

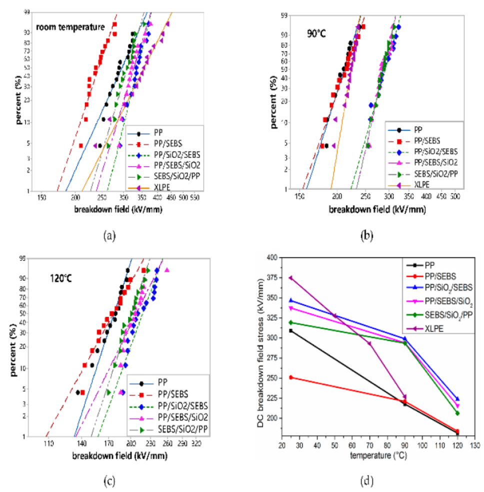


**Figure 16.** Weibull distribution plot of breakdown strength of XLPE, PP, and its composites **(a)** at room temperature, **(b)** at 90°C, **(c)** at 120°C, **(d)** at different temperature breakdown strength of materials[29].

## 4. Future Scope

Currently, XLPE is a standard material for power cable insulation. However, the problem with XLPE is that it is a non-recyclable material. Recyclable polymers are now the central area of focus for power cable insulation to improve the sustainability of the environment. Several options for polymer recycling technology have now been introduced. It includes mechanical and chemical recycling, waste-to-energy approaches, and bio-based polymers. Several thermoplastic polymers are also proposed to replace XLPE. PP is a promising cable material due to its high thermal resistivity, mechanical strength, and dielectric properties. PP is a thermoplastic material that can easily be reshaped, remould and reused correctly, which keeps our environment more sustainable.

## 5. Conclusions

This article reviewed recyclable cable insulation materials. In the future, PP can be a promising polymeric material as it is a cost-effective material with various advantages required for power cable insulation. Generally, thermoplastic polymers are suitable for recyclable cable insulation as they can be reshaped and reused. It has been seen that the incorporation of nanofillers into polymer matrix can improve the properties of polymers. Moreover, recyclable polymers are the future for cable insulation systems to maintain the sustainability of the environment.

## 6. Acknowledgment

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