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Advances in LDPE Nanocomposites for Photodegradation: Strategies, Mechanism and Applications

Zill-e-Huma[1], A. Ali[1], R. Bibi[2], U. Yunus[1]
[1] Department of Chemistry, Allama Iqbal Open University, H-8, Islamabad, 44000, Pakistan
[2] School of Biological Sciences, Victoria University of Wellington, New Zealand.
*Correspondence author Email: zill-e-huma@hotmail.com

ABSTRACT

Plastic waste generated from the widespread use of low-density polyethylene (LDPE) has raised significant environmental concerns due to its slow degradation. This review article explores the progress in LDPE nanocomposites for photodegradation, emphasizing strategies, mechanisms, and applications. Incorporating inorganic nanoparticles like titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_2O_3) into LDPE has been examined to enhance its properties and biodegradability. These nanoparticles strengthen LDPE's mechanical, thermal, and barrier characteristics, thereby improving its overall performance. Various techniques have been employed to optimize the concentration and size of nanoparticles to attain the desired properties. Photodegradation, employing sunlight to break down LDPE into smaller fragments, has effectively decomposed plastic waste and reduced its environmental impact. Artificial UV light sources and additives like sensitizers and biological agents such as enzymes and microorganisms can enhance photodegradation. The incorporation of inorganic nanoparticles in LDPE significantly improves its properties and biodegradability. Research into LDPE nanocomposites for their degradation under sunlight shows potential in addressing the environmental challenges caused by plastic waste. This advancement opens the door to a wide range of applications for LDPE nanocomposites, offering a sustainable alternative to traditional plastics.

Keywords: low-density polyethylene, photodegradation, nanoparticles, polymers, plastics.

1. INTRODUCTION:

"Plastic" from the Greek "plastikos," meaning moldable, is the popular term for a variety of synthetic or artificial polymers [1, 2]. Polyethylene is considered a commodity plastic due to its versatile properties like strong water resistance, durability, and lightness. These properties render them highly favoured and widely utilized in diverse consumer and industrial sectors [3]. It can be classified into several types like: low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), and ultra-high molecular weight polyethylene (UHMWPE). Among all of them LDPE shows more chemical resistance to acids, bases, strong oxidizing and reducing agents [4, 5]. Despite having many good traits possessed by LDPE, like flexibility, durability, and lightweight properties, but in high heat, it may break down quickly, not giving its best performance [6]. The most important property of a polymer is that it is recyclable and can be used to make new products. This makes it best for use in applications where moisture is present. LDPE is a plastic waste that contributes to environmental pollution and takes a long time to degrade [7, 8]. As illustrated in Figure (1), world plastic production has consistently increased, with a compound annual growth rate of 8.4% since 1950. In 2018, the annual plastic production was 360 million tons and is anticipated to reach 500 million tons by 2025 [9, 10].

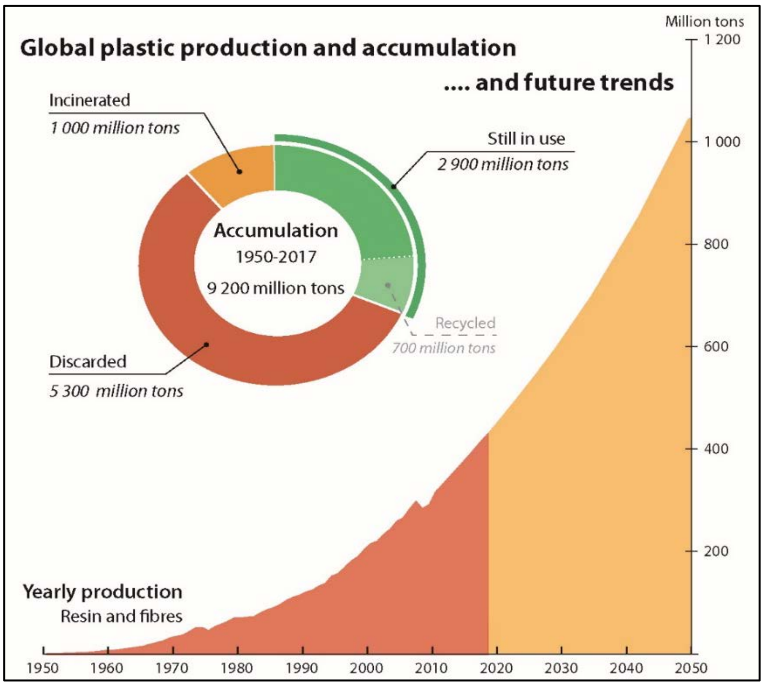

Figure 1: Annual production of plastic [10]

LDPE, a type of plastic, adds to environmental pollution and decomposes slowly. Improper disposal of plastic waste in the environment and the lack of effective waste management systems can lead to significant issues for land and marine animals. This includes threats such as entanglement, asphyxiation, and ingestion [11]. Several methods have been employed to address this issue, like:

a) **Biodegradation:** the action of microorganisms [12]
b) **Photodegradation:** the action of light [13]
c) **Thermal degradation:** the action of high temperature [14]
d) **Catalytic degradation:** the action of the catalyst [15]
e) **Hydrolysis:** reaction with water [16]

All these methods have some limitations, like biodegradation, which has a slow degradation rate which can vary depending on environmental conditions. This process can release greenhouse gases that contribute to pollution through leachate or runoff [16]. To enhance the biodegradation process, there is a need to identify microbes possessing a high active potential for polymer matrix [17]. Thermal degradation of plastics is highly dependent on the temperature and can vary based on the specific technique and type of plastics used. Environmental conditions also play a significant role in altering the thermal degradation process. In hot and dry environments, the weathering process tends to slow down [18].

Additionally, the presence of oxygen has a prominent impact on the thermal stability of plastics compared to inert atmospheres [19]. Among all of them, photodegradation causes more significant physical and chemical changes in the molecule [20, 21]. It involves the breakdown of the polymer chain through ultraviolet (UV) radiation, forming smaller fragments that can be degraded by microorganisms in the environment. With proper waste management and utilization of such methods, LDPE waste can be effectively managed and degraded to minimize its environmental impact [22, 23].

Nanoparticles have gained significant importance because of their ability to withstand adverse processing conditions and improved mechanical and chemical stability at high temperatures and pressures to overcome the world's most important challenges, that is, energy shortage and environmental pollution [24, 25, 26]. Nanocomposites are small-sized materials identified based on their sizes rather than their chemistry. These are also called nanometre-scale materials, as their particle size range is 1 nm to 100 nm. For LDPE waste management, incorporating Nanoscale particles into a polymer matrix can improve biodegradability and increase the efficiency of the photodegradation process [27, 28]. The addition of nanoparticles increases the surface area of the polymer, making it more accessible to UV radiation and microorganisms in the environment [29, 30]. The green synthesis of metal nanoparticles provides a cost-effective, straightforward, and environmentally friendly substitute to traditional chemical and physical procedures, generating high yields without complicated reagents or sophisticated equipment [31, 32, 33, 34]. The unique properties of nano-sized metal oxides, such as their high surface area and catalytic activity, can improve the overall performance of LDPE. Studies have shown that the addition of metal oxides, such as titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_2O_3), to LDPE, can enhance its tensile strength, elongation at break, thermal stability, and UV resistance [35, 36, 37]. However, incorporating metal oxides can also have negative effects, such as decreasing the transparency and increasing the brittleness of LDPE composites. Therefore, the concentration and size of nanoparticles must be optimized to achieve the desired properties [38, 39, 40, 41].

1.1. Methods for the degradation of LDPE:

Various methods for the disposal of plastic waste are used, such as landfilling, incineration, and recycling [42].

1.2. Landfilling:

LDPE landfilling is a common disposal method for plastic waste, including their products. Approximately 79% of plastic waste is sent to landfills [43]. When LDPE is disposed of in landfills, it is typically buried underground and stored alongside other types of waste. This method often collects LDPE waste through municipal waste management systems. It is compacted within the landfill to reduce its volume and maximize the available space, increasing the volume of waste over time. LDPE is a relatively inert material and does not readily decompose under typical landfill conditions. Its low reactivity and resistance to biological degradation contribute to its long-term stability within landfills [44]. While landfilling is a widely used disposal method, it has certain environmental considerations. Over time, LDPE waste in landfills can release greenhouse gases, such as methane, oxides of carbon and nitrogen, and hydrogen sulphide [45] due to anaerobic decomposition processes. Methane is a potent greenhouse gas that contributes to climate change. Modern landfills often incorporate gas collection systems to capture and utilize or burn methane for energy generation, mitigating its environmental impact.

Additionally, it requires proper management and monitoring to minimize potential environmental risks [46]. In addition to the environmental considerations, there are social and economic aspects to landfilling LDPE waste. Communities near landfills may experience adverse effects on their quality of life, including odour, noise, and visual impacts. Furthermore, the costs associated with landfill maintenance, monitoring, and closure can be significant and may burden local governments and waste management authorities. Considering these environmental, social, and economic aspects, proper management, monitoring, and exploration of alternative waste disposal methods are crucial to minimize the potential risks associated with LDPE landfilling.

1.3. Incineration:

Incineration of LDPE**,** a widely adopted waste-to-energy technique, is implemented worldwide to convert approximately 750,000 metric tons of solid waste daily into heat energy [47]. LDPE waste is often carried out in waste-to-energy facilities. LDPE waste is subjected to high temperatures in an incinerator, typically between 800°C and 1200°C (1,472°F and 2,192°F). The high temperatures, combined with the supply of oxygen, facilitate the combustion of LDPE, converting it into carbon dioxide (CO_2) and water vapour (H_2O) as the primary by-products. The primary objective of incineration is to convert the waste into energy in the form of heat and electricity [48]. After LDPE incineration, the remaining solid waste, known as bottom ash, is collected and processed. The ash typically contains non-combustible materials, such as inorganic compounds and metals, which require proper disposal. It is often sent to specialized landfills or undergoes further treatment to recover valuable metals [49]. However, it is important to know that incineration, which involves the incomplete combustion of plastic and solid waste, can lead to significant health issues due to the formation of toxic gases such as dioxins ($C_4H_8O_2$), furans (C_4H_4O), carbon monoxide (CO), and various polyaromatic hydrocarbons. These substances can potentially cause carcinogenic effects in humans [50].

1.4. Recycling:

Recycling LDPE is also one of the strategies to reduce plastic waste and promote sustainability. A constant increase in virgin plastic production and waste puts our natural environment at risk of plastic pollution and greenhouse gas emissions [51]. LDPE can be recycled into new products through various methods, including primary and secondary mechanical, tertiary chemical recycling (tertiary recycling) and down cycling [52]. All these methods have certain disadvantages and risks. For instance, incineration and landfilling can be an effective method for waste disposal yet have certain environmental considerations. For recycling, distinguishing LDPE from other plastics during sorting, contamination from food residues or incompatible materials, and the presence of additives or colourants greatly impact the recyclability of LDPE [53]. Improper use of plastic waste in Third World Countries, like burning it, as in several parts of Asia and Africa, harms the environment and people's health. Also, recycling plastics is challenging because of money issues, not sorting waste well, using lots of energy, mixing it with other stuff, and cleaning problems [54]. Thus, in recent years, there has been an increased focus on reducing plastic waste generation, promoting and developing more sustainable alternatives to plastics, and aiming to minimize the need for incineration and landfilling LDPE and other plastic waste, a key objective [55]. Consequently, alternative strategies for degrading plastic waste, such as biotic and abiotic degradations, have been developed.

1.5. Biotic and Abiotic degradation:

The biotic degradation of LDPE by microorganisms typically involves surface colonization, followed by the secretion of enzymes that can initiate chain scission of the polymer. The resulting breakdown products are smaller fragments of LDPE. Since 1980, technical research and development has focused on eliminating plastics before recycling, segregation, or reclamation efforts. These techniques have been aimed at developing biodegradable plastics [56]. *Penicillium chrysogenum*, *Penicillium oxalicum* fungus, Biofilm forming (*Rhodococcus ruber*), thermophilic (*Brevibacillus borstelensis*) bacteria were found to be a potential candidate for the biodegradation of polyethylene. However, complete mineralization of LDPE into carbon dioxide and water is rare. It's worth noting that the biodegradation of LDPE by microorganisms is relatively slow, and the process may require favourable environmental conditions, including appropriate temperature, moisture, and nutrient availability [57]. While LDPE is not readily biodegradable by most microorganisms, certain specialized bacteria can degrade LDPE to some extent. These bacteria belong to various genera, such as *Pseudomonas*, *Bacillus*, and *Sphingobium*. These microorganisms can produce enzymes, such as esterase and lipases, that can partially break down LDPE's polymer chains. Studies showed that UV exposure plays a key role in inducing the fragmentation process of polymeric materials, namely biodegradables [58].

A team of scientists discovered that when they exposed pretreated polyethylene (PE) to nitric acid, *Pseudomonas aeruginosa* and *Microbacterium paraoxydans* achieved biodegradation rates of 50.5% and 61% (Figure 2), respectively [59].

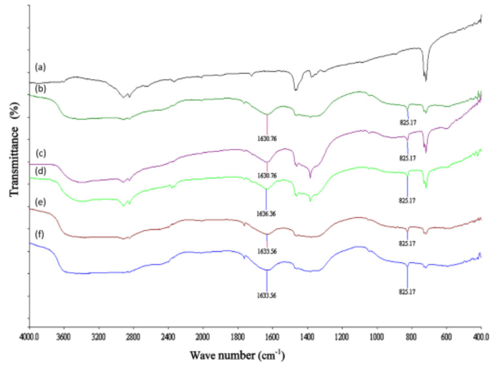

Figure 2: FTIR spectral image of nitric acid pretreated LDPE powder at different concentrations [59]

Another study revealed that when microorganisms were given pretreated PE treated with UV and nitric acid, there was a weight loss of up to 27.3%. Although chemical pretreatment of plastic, either alone or in conjunction with other methods, effectively breaks down and degrades plastic, it is not considered environmentally friendly due to its negative impact [60]. In natural environments with limited access to oxygen (anaerobic conditions), such as landfills or marine sediments, the biodegradation of LDPE is even more challenging due to the absence of oxygen-dependent microbial activity [61].

Abiotic degradation refers to the breakdown or transformation of substances in the environment without the involvement of living organisms. This process can occur through various mechanisms, such as photolysis (degradation by light), hydrolysis (degradation by water), oxidation (degradation by oxygen or other chemicals), hydrothermal liquefaction and chemical hydrolysis (enzymes, acids, bases, and solvents) [62].

In general, the abiotic degradation process is likely to lead to biodegradation due to less bioavailability of plastics. The biodegradation mechanism is complex and involves living sources [63]. In the case of plastics, their leftovers may require bio-assimilation as a vital but not sole requirement for technological applications. Generally, plastics necessitate a controlled lifespan before undergoing physical degradation. During an induction period, there is expected to be no alteration in the physicochemical and mechanical properties of the plastics [64]. While abiotic degradation can contribute to the breakdown of pollutants in the environment, it has certain drawbacks that must be considered. The lack of selectivity, variations in efficiency, environmental factors, incomplete mineralization, and practical limitations highlight the need for a cautious approach when relying solely on abiotic degradation for pollutant removal [65]. Integrating abiotic degradation with other remediation approaches and considering the specific context and characteristics of pollutants can help develop more effective and sustainable strategies for environmental remediation [66].

1.6. Photodegradation:

The approach towards photodegradation is attractive due to its role in transforming harmful substances, impact on environmental quality, potential for degrading emerging contaminants, and compatibility with sustainable remediation approaches [67]. Photodegradation of plastics mainly takes up a free radical mechanism initiated by solar radiation. The UV radiation frequency utilized by the plastic for their degradation ranges between UV-B (290-315 nm) and UV-A (315-400 nm) [63]. Photodegradation of LDPE is difficult due to the absence of chromophores. The presence of impurities and or structural malfunction within the polymer during the manufacturing process or due to weathering can function as chromophores [68]. Carbonyl groups within the LDPE structure can act as chromophores followed by the Norish type I and Norish type II reactions; radicals generate vinyl ketone groups responsible for main chain scission [69]. The information provided emphasizes the necessity for further research into plastic degradation due to the intricate interplay of various factors that influence the initiation and speed of degradation. Utilizing nanoparticles for photodegradation appears as a promising technique for breaking down plastics. This method offers an environmentally friendly and cost-effective solution [70]. By comprehending the molecular and environmental factors, new principles can be developed to create more efficient and successful photodegradable plastics. Consequently, the significance of employing nanoparticles for photodegradation lies in their ability to tackle the challenges associated with plastic waste management, providing a sustainable and eco-friendly approach that significantly mitigates the environmental impact of plastic waste [71, 72].

In recent years, researchers have explored using other materials, such as graphene, carbon nanotubes and organic dyes, as additives to enhance the photodegradation of LDPE. Graphene and carbon nanotubes possess excellent photocatalytic properties, primarily attributed to their large surface area, high electron mobility, and unique electronic structure [73]. These properties enable them to efficiently capture photons and generate electron-hole pairs upon light absorption, leading to increased reactivity and catalytic activity in photodegradation processes [74]. Graphene and carbon nanotubes can generate reactive oxygen species, such as singlet oxygen ($1O_2$) and hydroxyl radicals ($^{\bullet}OH$), under light irradiation. These reactive oxygen species (ROS) are highly reactive and can oxidize the LDPE polymer chains, leading to chain scission and degradation. Their unique properties and interactions with light make them promising materials for improving the efficiency of LDPE photodegradation processes. However, further research is still needed to optimize their incorporation and utilization in practical applications and better understand their long-term effects on the environment [75].

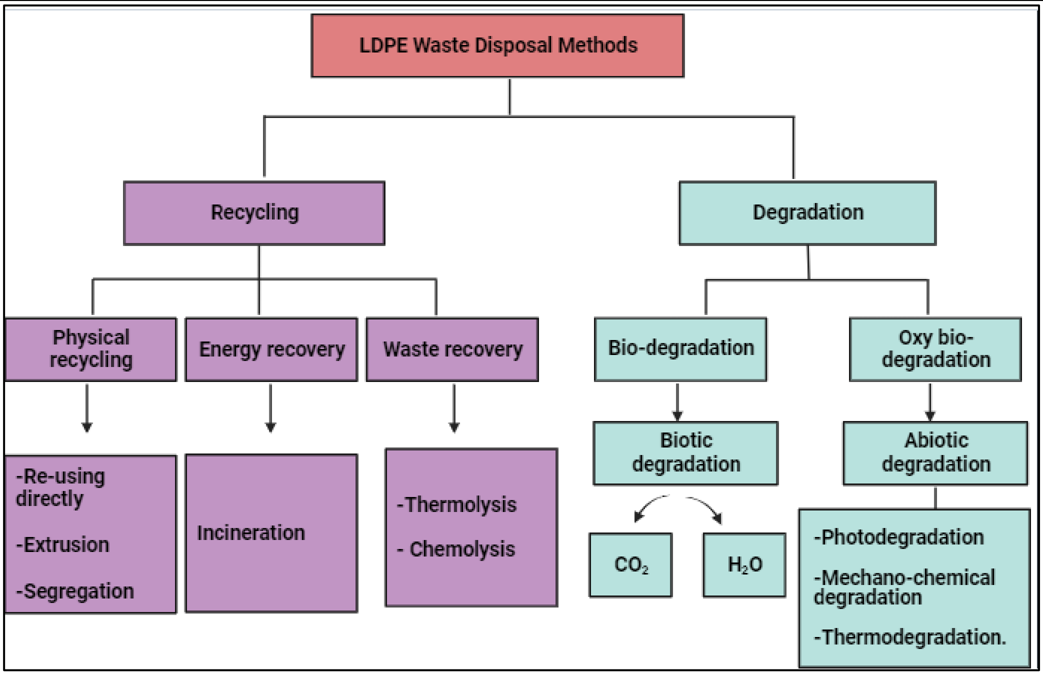

Figure 3: **LDPE Waste Disposal Flow Chart**.

Table 1: Effects of Degradation on Different Types of LDPE:

Degradation Mode	Type of LDPE	Morphological Change	Functional Change	Mechanical change: % Elongation	Mechanical change: % Tensile Strength	FTIR (cm^{-1})	References
Biodegradation	LDPE with marine bacteria	Reduction in crystallinity	Ketones/ decrease in carbonyl indices	-12%	-15	1733-1743	[76, 77]
	Monitor environment after 10 years	Rough surface with cracks and grooves	Esters	-4%	-16.4	1448-1470 & 2800-300	[78, 79]
	P. chrysosporium in soils with LDPE & 12% starch	Formation of Biofilm on the surface of LDPE, increasing microbial activity with 26% surface hydrophobicity and 31% hydrolytic activity that produces few holes by starch disintegration	Carbonyl compounds , primary & secondary alcohols	62%	-51%	1,650–1,860 & 900–1,200	[80, 81, 82]
Photo-oxidation	PE with vinyl and *t*-vinylene groups	Formation of microcracks on surface of LDPE in localized and interconnecting pattern, Polymer surface fractures observed due to chain scission reaction. After just a few weeks of exposure, LDPE film undergoes significant changes, becoming notably more brittle.	Ketones, acids, esters, and lactones	±10% /±30%	230 ± 10/300 ± 30	1660 & 1712-1723 & 1733-1743	[83, 84, 85]

1.7. Mechanism of Photodegradation by Nanocomposites

The photodegradation of LDPE involves a complex series of chemical reactions initiated by the absorption of UV light. The primary mechanism of photodegradation in LDPE can be explained as follows:

1. **Absorption of UV Radiation**: LDPE contains carbon-carbon (C-C) and carbon-hydrogen (C-H) bonds in its polymer chain. When LDPE is exposed to UV radiation, particularly in the range of 280-340 nm (UVB and UVA wavelengths), the polymer absorbs energy from the UV light.
2. **Excitation of Electrons:** The absorbed UV energy excites the electrons in LDPE molecules, promoting them to higher energy levels. This leads to the formation of excited states within the polymer [54].

$$R'-R''- \xrightarrow[\text{nanoparticles}]{h\nu} (R'-R'')^*$$

$$(R'-R'') \longrightarrow R'^{\bullet} + R''^{\bullet}$$

3. **Formation of Free Radicals:** The excited LDPE molecules undergo a process called homolytic cleavage, where the energy is redistributed, and weak bonds within the polymer chain are broken. This results in forming free radicals, which are highly reactive species with unpaired electrons [54].

$$R-O-OH \xrightarrow{h\nu} RO^{\bullet} + HO^{\bullet}$$

$$RO-OR \xrightarrow{h\nu} RO^{\bullet} + RO^{\bullet}$$

4. **Chain Scission:** The free radicals formed during photodegradation can initiate a chain reaction by attacking neighbouring LDPE molecules. This process is known as chain scission, where the polymer chains are broken into smaller fragments. The newly formed radicals can further propagate the degradation process by attacking other LDPE chains, leading to a cascading effect.

$$RO^{\bullet} + R' \longrightarrow ROH + R'^{\bullet}$$

$$HO^{\bullet} + R' \longrightarrow H_2O + R'^{\bullet}$$

5. **Oxidation:**
As the photodegradation progresses, the free radicals react with atmospheric oxygen (O_2) to form peroxy radicals. These peroxy radicals can react with LDPE, causing further chain scission and promoting oxidation reactions. Oxidation leads to the introduction of oxygen-containing functional groups, such as carbonyl (-C=O) and hydroperoxide (-OOH), in the LDPE structure [54].

$$R'^{\bullet} + O_2 \longrightarrow ROO^{\bullet}$$

$$ROO^{\bullet} + RH \longrightarrow ROOH + R^{\bullet}$$

6. **Crosslinking**
In addition to chain scission and oxidation, photodegradation can induce crosslinking reactions in LDPE. Crosslinking occurs when the free radicals recombine to form covalent bonds between LDPE chains. This can result in forming a three-dimensional network structure within the polymer, leading to increased stiffness and brittleness [54].

$$ROOC^{\bullet} + HR^{\bullet} \longrightarrow ROCOH + RCOH + ROR$$

7. **Changes in Physical Properties**
The combined effects of chain scission, oxidation, and crosslinking result in various physical and chemical changes in LDPE. These changes include discoloration, surface cracking, loss of mechanical strength, reduced flexibility, and overall degradation of the material's properties [55, 56, 57].

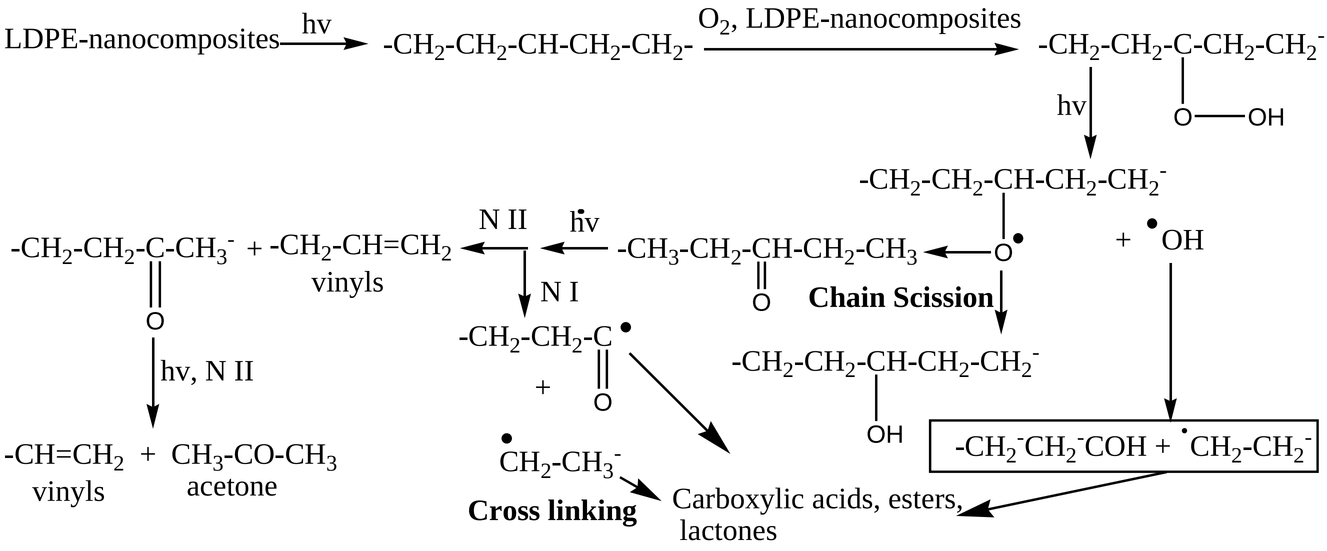

Figure 4: Scheme for the Photo-oxidative degradation of LDPE [57]

1.8. Applications of Nanoparticles as Photocatalysts

Some important applications of LDPE nanocomposites are summarized in Table 2, given below.

Table 2: Overview of LDPE Nanocomposites (NC)

LDPE NC	Properties	Effectiveness	Applications	References
LDPE + TiO_2	Dielectric relaxation, photocatalytic, high surface area	Effective, but limited by need for UV light	Engineering, packaging, UV-protections, antimicrobial coating.	[58]
LDPE + SiO_2	High surface area, good biocompatibility, stable under a wide range of conditions	Effective in enhancing degradation, especially when functionalized with organic groups	Barrier films, Flame retardant, Mechanical reinforcement, Environmental remediation	[59]
LDPE + Al_2O_3	Improved mechanical strength, enhanced thermal stability	Barrier packaging for sensitive products	Electrical insulation, automotive components, interior trim and structural parts, power engineering	[60]
LDPE + ZnO	Photocatalytic, antimicrobial	Effective, but limited by potential toxicity	Antibacterial coating, photocatalysis, gas sensors, energy storage	[61]
LDPE + $BiFeO_3$	Controlling the spontaneous magnetization by electric field	High dielectric constant, multi-ferric behavior	Wastewater treatment technology, flexible electronics, biomedical devices, energy harvesting	[62]
LDPE + CNTs	High mechanical strength, electrical conductivity, thermal stability	Reinforcement, electrical conductivity	Aerospace and automotive, electrical and electronics, packaging, and energy storage, biomedical	[63]
LDPE + Chitosan NPs	Biocompatibility, barrier properties	Enhanced mechanical properties, antibacterial activity, biodegradability	Food packaging, biomedical and healthcare, environmental applications contributing to a reduction in plastic waste and environmental pollution, water treatment, textiles, and coatings	[64]
LDPE + GO NPs	Mechanical strength, thermal stability, electrical conductivity	Barrier properties, electrical conductivity enhancement	Packaging material, UV radiation, energy storage, conducting films and coatings, sensing devices, aerospace and automotive	[65]
LDPE + Au	Optical properties, mechanical flexibility, electrical conductivity	Plasmonic enhancement, biomedical applications, catalysis	Sensor technology, packaging and food industry, optoelectronics, energy storage	[66]
LDPE + Ag	Antimicrobial, electrical conductivity, thermal stability	Antibacterial properties, conductive applications, enhanced mechanical strength	Healthcare and biomedical devices, packaging and food industry, environmental applications, energy storage	[67]

LDPE + Zeolites	Adsorption capacity, thermal stability, mechanical strength	Gas separation and purification, effective in removing VOCs from air and water, controlled release system	Environmental remediation, packaging and food industry, industrial processes, energy storage	[68]
LDPE+Nanocellulose	Mechanical properties, barrier properties, thermal stability	Improved mechanical performance, sustainable and biodegradable	Packaging materials, biomedical materials, paper coating, composite materials, environmental and agricultural applications	[69]
LDPE + MOFs	High surface area, surface versatility, chemical stability	Drug delivery system, catalysis, sensing, and detection	Environmental remediation, drug delivery and therapeutic, energy storage and conversion	[70]

2. Conclusions

Considering all the evidence, the use of LDPE nanocomposites offers a promising solution to mitigate the environmental impact of plastic waste. Materials derived from renewable sources reduce the environmental impact and contribute to the circular economy. The optimization of the photodegradation process, including factors such as nanomaterial size, shape, composition, and processing conditions, remains a challenge. The incorporation of nanomaterials into LDPE enhances its photodegradation ability, leading to the formation of environmentally friendly products. This technology aligns with the principles of green chemistry and contributes to a more sustainable future by reducing plastic pollution. Extensive research has been conducted on LDPE nanocomposites, focusing on enhancing their photodegradation efficiency and understanding the underlying mechanisms. Various nanomaterials, such as metal oxides, carbon-based nanomaterials, and biodegradable polymers, have been investigated for their compatibility with LDPE. They all have a few limitations, but SiO_2 nanoparticles can be more effective in enhancing degradation, especially when functionalized with organic groups. Surface modifications, including functionalization and coating, have also been explored to improve the dispersion and interaction between the nanomaterials and the LDPE matrix.

Renewable and sustainable nanomaterials, including cellulose nanocrystals, chitin, or lignin, offer a greener alternative for LDPE nanocomposites. Various experimental techniques have been applied for effective understanding of photodegradation processes. Among them are spectroscopic techniques (FTIR, UV-visible spectroscopy), chemical techniques (GC-MS, HPLC) and microscopic techniques (SEM, TEM & STEM). Using a combination of spectroscopic, chemical analysis, and microscopy techniques, researchers can understand the changes that occur during photodegradation and develop effective strategies for reducing the environmental impact of plastics.

Future Directions

Green chemistry presents an opportunity to develop more sustainable plastic materials that can be effectively degraded and recycled, contributing to a more circular economy and waste reduction. The future of LDPE nanocomposite research lies in developing scalable and cost-effective manufacturing processes, integrating them into practical applications, and establishing regulatory frameworks. Technological advancements, such as surface modification techniques and characterization methods, will contribute to optimizing LDPE nanocomposites' performance, durability, and recyclability.

Recent studies have demonstrated the development of novel nanomaterials with unique properties, such as plasmonic nanomaterials, which show potential in enhancing the photodegradation process. Further research is needed to understand the intricate mechanisms and to develop innovative techniques for studying photodegradation. Collaborative efforts among researchers from various disciplines are crucial to accelerate progress in this field and address regulatory considerations and standards for the safe and responsible use of LDPE nanocomposites. The development of novel nanomaterials, advancements in surface modifications, and the utilization of renewable and sustainable alternatives demonstrate the innovative nature of LDPE nanocomposite research. Continued research and innovation in this field will undoubtedly lead to breakthroughs and solutions, ensuring LDPE nanocomposites' long-term viability and environmental friendliness. Let us strive to foster a cleaner and greener world for generations.

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