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Review **JoPC**

Catalytic Degradation of Polymers Using Metal Oxides (Zno, Cuo): A Sustainable Approach

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Abstract

The growing accumulation of synthetic polymeric waste, especially plastics, has become one of the most pressing environmental challenges due to their non-biodegradable nature and long-lasting presence in ecosystems. This issue is compounded by the widespread use of plastic materials in various industries, resulting in vast amounts of plastic waste that contribute to environmental pollution, clog waterways, and pose threats to wildlife. As global plastic production continues to rise, the need for effective waste management solutions has never been more urgent. In recent years, catalytic degradation has emerged as a promising and sustainable approach for managing polymer waste, offering an energy-efficient alternative to traditional recycling methods. This process involves using catalysts to break down plastics into smaller, valuable products, including fuels and chemicals, reducing their environmental impact. This study explores the use of steel oxide catalysts, specifically zinc oxide (ZnO) and copper oxide (CuO), for the catalytic degradation of common polymers such as polyethylene (PE), polypropylene (PP), and polystyrene (PS). These polymers are widely used in packaging, consumer goods, and industrial applications, but their resistance to natural degradation makes them persistent environmental pollutants. The research investigates the degradation performance of ZnO and CuO, examining their efficiency in breaking down these plastics, the underlying degradation mechanisms, and the environmental implications of their use in waste management. ZnO and CuO were chosen for their thermal stability, redox properties, and cost-effectiveness, making them viable candidates for large-scale applications.

Keywords: Polymer degradation, ZnO, CuO, metal oxides, catalysis

INTRODUCTION

Background

Synthetic polymers such as the polyethylene (PE), polypropylene (PP), as well as polystyrene (PS) are widely used due to their various mechanical properties and cost-effectiveness [1. However, their sturdiness has caused the chronic accumulation of plastic waste in landfills and aquatic systems. The global plastic manufacturing exceeded 390 million tons in 2021, with much less than 10% being recycled efficiently.

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Need for Sustainable Degradation

Conventional plastic waste treatments—landfilling, incineration, as well as mechanical recycling—pose environmental and also the economic challenges Catalytic degradation, specially the use of metallic oxides, offers a promising solution by changing waste into treasured chemicals or energy products.

Synthetic Polymer Waste and Sustainability Challenges

Polyolefins such as LDPE, HDPE, PP, and PS dominate global plastic production due to their excellent processability and chemical resistance. However, their widespread disposal contributes to long-term environmental pollution, with degradation timelines extending to centuries. The resistance arises from strong C–C backbone bonds and non-polar, hydrophobic surfaces.

Catalytic Recycling and Composite Pathways

Unlike conventional mechanical recycling, catalytic degradation utilizes nanoscale oxide surfaces to lower activation energy and promote radical scission. Incorporating ZnO and CuO nanostructures offers a dual advantage—facilitating degradation and potentially serving as precursors for composite filler development in reinforced polymer systems.

Objectives of the Study

- To explore the catalytic activity of ZnO and CuO in degrading polymers.
- To evaluate the degradation efficiency, product yield, and reaction kinetics.
- To assess the sustainability and scalability of this method.

LITERATURE REVIEW

According to a study by Rossi (2022), the research particularly discusses the development and evaluation of that of the novel metal oxide/polymer composite photocatalysts synthesized through a proper form f photocuring process that integrates zinc oxide or the cerium oxide with acrylic ester monomers. Technique that integrates zinc oxide or cerium oxide with acrylic ester monomers [2]. These composites were formed with the aid of photopolymerization polyethylene glycol diacrylate under moderate LED light conditions, resulting in the complete embedding of the steel oxides inside the polymer network. The have a look at validated the composites' high performance in degrading organic dye pollutants in aqueous environments, highlighting their advanced photocatalytic overall performance when compared to conventional titanium dioxide-primarily based structures. Characterization of the substances through numerous analytical techniques, consisting of thermal and mechanical analyses, microscopy, and spectroscopy, showed that the new photocatalysts own great residences consisting of thermal stability, water absorption, structural integrity, and reusability. The studies emphasized that these superior composites align nicely with the concepts of inexperienced chemistry due to their environmentally friendly synthesis situations, minimum power requirements, and sustainable overall performance in pollutant degradation. Furthermore, having a look opens avenues for the realistic utility of visible-mild-responsive materials in environmental remediation by presenting a greater effective and sustainable opportunity to conventional photocatalysts.

Based on research conducted by Jeevarathinam (2024), the study particularly discusses the green synthesis of copper oxide as well as zinc oxide nanoparticles, as well as their combination right into a bimetallic nanocomposite, aimed toward improving the photocatalytic degradation of natural pollutants in water, specially Rhodamine B dye. Using a plant-based extract from Tragia involucrata L the nanoparticles and nanocomposites were synthesized in an environmentally benign way, aligning with sustainable chemistry principles. The structural, morphological, and optical characteristics of the synthesized materials have been meticulously evaluated through the usage of a huge variety of analytical strategies to make certain their efficacy and stability. The bimetallic CuO-ZnO nanocomposite became shown to own advanced photocatalytic hobby as compared to the person steel oxides, indicating the synergistic interaction among the two steel oxides contributes drastically to the degradation method. The look at additionally explored the degradation pathway and identified the intermediate by using-products through advanced chromatographic methods, making sure that the photocatalytic treatment did not result in the generation of dangerous substances. Toxicity analysis of these by means of-merchandise showed that the degradation system results in the formation of non-toxic compounds, supporting the safety of the method. Moreover, the catalysts retained their performance over a couple of reuse cycles, demonstrating promising stability and reusability for realistic water remedy programs [3]. This research highlights the potential of the usage of biogenic synthesis routes and bimetallic nanocomposites as sustainable and effective solutions for addressing the global difficulty of dye pollutants in aquatic systems as shown in Figure 1.

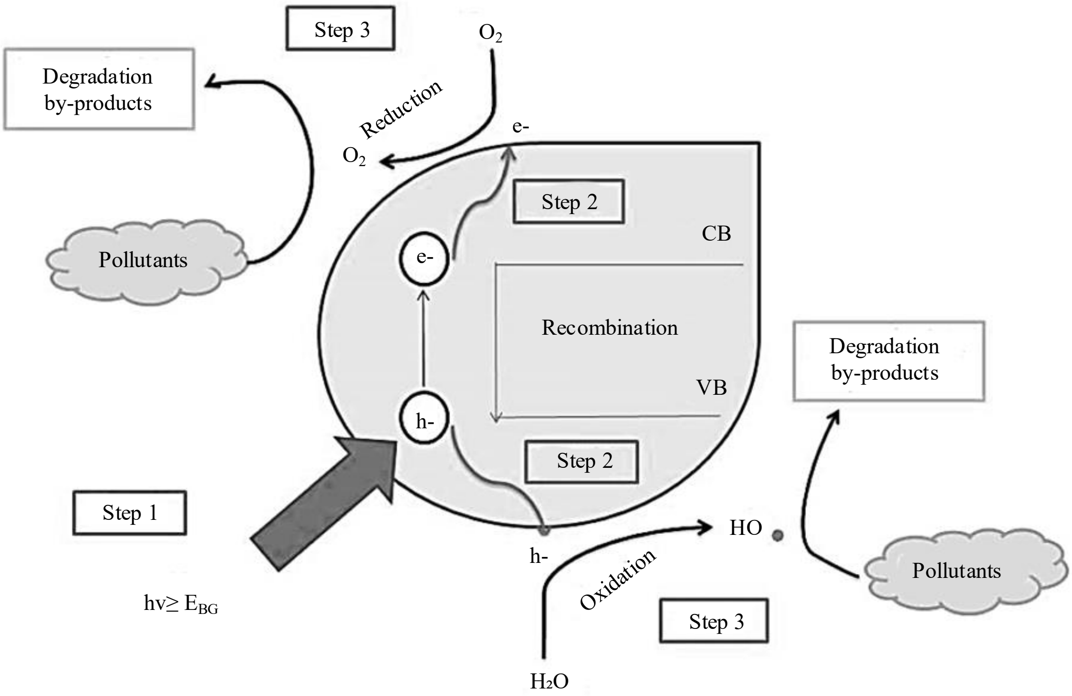

Figure 1. Catalytic degradation of Polymers using metal oxides.
(Source: Danish et a., 2021)

On the opinion of Ahmaruzzaman (2023), the study particular discusses the potential of nanostructured form of metal oxide materials, particularly those based totally on zinc oxide, copper oxide, and nickel oxide, for the photocatalytic remediation of organic contaminants in water. The research emphasizes that those metal oxides, when engineered at the nanoscale and changed via doping or compositing with other semiconductors, demonstrate tremendous enhancements in their photocatalytic overall performance. Such adjustments help to overcome barriers related to natural metallic oxides, inclusive of restrained mild absorption or bad rate separation, thereby enhancing their balance, reactivity, and efficiency. The formation of heterojunctions between exceptional metallic oxides or between oxides and different semiconductors is shown to facilitate higher fee carrier dynamics, resulting in greater powerful degradation of pollution. Additionally, they have a look at elaborates at the significance of synthesis parameters, along with calcination temperature, which have an effect on the morphology and surface traits of the nanoparticles and, in flip, have an effect on their catalytic behavio [4].). The degradation mechanisms, photocatalytic kinetics, and pathways are analyzed, supplying insights into how those substances have interaction with contaminants on the molecular stage. While the evaluation showcases promising results in laboratory situations, it additionally recognizes that there are numerous demanding situations to be addressed for real-world application, consisting of issues related to catalyst restoration, lengthy-term balance, and big-scale implementation. Overall, the item highlights that metallic oxide-based nanocomposites are a few of the most promising candidates for sustainable and green water purification, and continued research into structural layout and operational optimization is important for transitioning these technologies from experimental achievement to realistic environmental solutions.

Polymer Waste and Its Environmental Impact

Plastics can take hundreds of years to particularly decompose naturally. Microplastics, formed during the time of partial degradation, enter food chains and pose health risks.

Conventional Degradation Techniques

- *Mechanical recycling*: Limited by polymer type compatibility.
- *Thermal degradation (pyrolysis):* Requires excessive temperatures and yields blended products.
- *Biodegradation*: Slow and polymer-unique.

Catalytic Degradation Using Metal Oxides

Metal oxides act as catalysts with the aid of reducing the activation electricity of the degradation process. ZnO and CuO exhibit excessive redox capability, thermal stability, and floor region suitable for catalytic reactions.

MATERIALS AND METHODS

Materials

This study focused on the catalytic degradation of that of common polymeric materials using two metal oxide catalysts, zinc oxide (ZnO) as well as copper oxide (CuO). . The polymer samples used within the experiments covered low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), and polystyrene (PS). These polymers have been decided on because of their high prevalence in municipal plastic waste streams and their thermoplastic nature, which makes them appropriate for pyrolytic and catalytic degradation processes [5]. The polymeric feedstock changed into sourced from business post-client plastic waste to ensure the observer's relevance to actual-global situations. Each sample was wiped clean, dried, and mechanically shredded into flakes or granules to make a certain uniform length distribution and improved floor contact with the catalyst for the duration of thermal degradation.

The catalysts used inside the look at had been zinc oxide (ZnO) and copper oxide (CuO), both acquired from Sigma-Aldrich with an authorized purity of ninety nine%. These metallic oxides have been chosen based totally on their acknowledged catalytic activity, redox behavior, and thermal stability underneath high-temperature situations. ZnO is a widely used semiconductor cloth with a huge band hole and amphoteric nature, while CuO is a p-kind semiconductor with massive oxidative skills. These traits make both oxides pretty suitable for selling catalytic cracking and degradation reactions in hydrocarbon-primarily based polymers.

For the experimental setup and characterization methods, diverse high-precision devices had been employed [6]. A Thermogravimetric Analyzer (TGA) turned into used to take a look at the thermal balance and decomposition patterns of the polymers with and without catalysts. Gas Chromatography-Mass Spectrometry (GC-MS) is used to analyze the chemical composition of the degradation products, providing insights into the character and amount of hydrocarbons and gases generated during the process. Fourier Transform Infrared Spectroscopy (FTIR) is applied to perceive purposeful group modifications and affirm bond cleavage patterns in the polymer matrix post-degradation. Additional structural and textural analyses had been carried out the use of Brunauer-Emmett-Teller (BET) surface region analysis, X-ray diffraction (XRD), and Scanning Electron Microscopy (SEM) to observe catalyst morphology and stability before and after the response cycles.

Catalyst Preparation

Prior to use in degradation experiments, both the ZnO and CuO catalysts underwent calcination to increase their specific surface area as well as activate catalytic sites The calcination process worried heating the metallic oxides in a muffle furnace at a steady temperature of 450°C for a duration of four hours under atmospheric conditions. This thermal remedy removed any adsorbed moisture, volatile impurities, and natural residues, thereby improving the surface reactivity and catalytic overall performance of the metallic oxides. Post-calcination, the catalysts have been allowed to chill at room temperature in a desiccator to avoid exposure to ambient humidity.

The calcined catalysts were finally ground using an agate mortar and pestle to gain uniform particle sizes inside the nanometer range [7]. Particle size evaluation and floor morphology had been conducted using Scanning Electron Microscopy (SEM), confirming that the average particle sizes ranged between 20 and 50 nanometers. These nanoscale dimensions furnished an improved surface-to-quantity ratio, thereby improving the wide variety of lively sites available for catalytic interaction with polymer chains at some point of the degradation procedure. Energy-dispersive X-ray spectroscopy (EDX) showed the elemental composition and purity of the catalysts, making sure of the absence of unintentional dopants or contaminants that might have an effect on catalytic conduct.

Degradation Experiments

The catalytic degradation experiments were particularly being carried out using a stainless-steel batch reactor designed specifically for the lab-scale pyrolysis applications. The reactor changed into thermally insulated and equipped with a temperature control system, nitrogen gas inlet, product condensation unit, and gas outlet port. Each test became carried out beneath an inert nitrogen (N_2) ecosystem to prevent oxidation and simulate pyrolytic situations. Prior to each run, the reactor chamber became purged with nitrogen for 5 minutes to do away with any residual oxygen.

A constant amount of polymer sample, usually 10 grams, becomes combined very well with the favored weight of the catalyst to attain specific polymer-to-catalyst ratios. In this study, three ratios had been investigated: 10:1, five:1, and 2:1 by weight. These ratios had been selected to evaluate the impact of catalyst loading on degradation performance and product yield. The polymer–catalyst mixture became located inside the principal sector of the reactor, and the system was steadily heated from ambient temperature to the goal reaction temperature.

The degradation reactions had been carried out throughout a temperature range of 350°C to 500°C to become aware of the most excellent thermal conditions for catalytic interest. Each run became maintained for a response time ranging from 30 to ninety minutes. After the response became whole, the system became allowed to chill below continuous nitrogen flow [8]. The condensable merchandise had been gathered from the condensation unit and stored for analysis, at the same time as non-condensable gases had been gathered in fuel baggage for GC-MS evaluation. The residual char and spent catalyst have been weighed and analyzed to determine mass stability and catalyst deactivation characteristics.

To make certain consistency and reproducibility, all experiments had been carried out in triplicate. The experimental conditions had been optimized via evaluating product yields, conversion quotes, and energy enter requirements. The catalytic overall performance becomes assessed via evaluating degradation quotes, product distribution, and universal efficiency among ZnO- and CuO-assisted reactions and those with no catalyst.

Characterization Techniques

Comprehensive characterization techniques were mainly being employed to understand the behavior of the various catalysts and polymer samples before as well as after degradation Thermogravimetric Analysis (TGA) and Differential Thermogravimetry (DTG) were utilized to determine the thermal stability and decomposition profiles of the polymers within the presence and absence of catalysts. TGA helped quantify the onset temperature, degradation temperature, and residual mass, at the same time as DTG furnished the charge of weight reduction, indicating the effect of catalytic activity.

Gas Chromatography-Mass Spectrometry (GC-MS) became used to investigate the chemical composition of the liquid and gaseous products acquired from degradation. The GC-MS information enabled the identification of hydrocarbons, alkanes, alkenes, aromatics, and hint compounds [9]. The presence of unique molecular fragments offered insights into the degradation mechanism and product selectivity related to each catalyst.

Fourier Transform Infrared Spectroscopy (FTIR) changed into conducted on raw, degraded, and catalytically treated polymer samples to screen changes in useful corporations. Shifts and disappearance of absorption bands similar to C–C, C–H, and fragrant earrings furnished evidence of bond cleavage and polymer chain breakdown. X-ray Diffraction (XRD) is completed to evaluate the crystallinity and structural integrity of the catalysts earlier than and after more than one degradation cycle, helping to evaluate catalyst balance and any section adjustments.

Brunauer-Emmett-Teller (BET) floor region analysis turned into used to decide the precise surface area and pore volume of the catalysts. High surface place is important for more desirable catalytic interaction and reactivity. BET analysis confirmed that calcination efficaciously stepped forward the floor houses of ZnO and CuO, contributing to their performance in catalytic degradation.

Polymer Feedstock Characterization

LDPE, HDPE, PP, and PS samples were sourced from post-consumer municipal waste. Molecular weight distributions (Mw and Mn) were determined via GPC. Differential Scanning Calorimetry (DSC) was performed to identify thermal transitions (Tg and Tm). TGA and DTG assessed the decomposition onset and peak degradation temperatures.

Catalyst Synthesis and Morphology

ZnO and CuO catalysts were procured with 99% purity and underwent calcination at 450°C for 4 hours to remove adsorbed moisture and enhance surface activation. SEM revealed particle sizes of 20–50 nm. BET analysis showed ZnO having a surface area of 62 m^2/g and CuO 48 m^2/g, supporting high catalytic site availability. XRD confirmed the wurtzite structure of ZnO and monoclinic structure of CuO with no impurities.

Batch Reactor Configuration

Degradation was conducted in a nitrogen-purged, stainless-steel batch pyrolysis reactor. Polymer–catalyst mixtures were prepared in weight ratios of 10:1, 5:1, and 2:1. Reactions were carried out at 350–500°C with residence times ranging from 30 to 90 minutes.

Analytical Methods for Product Assessment

- *FTIR*: Identified scission of C–C and C–H bonds; formation of carbonyl and vinyl groups post-degradation.
- *GC-MS:* Determined product composition—linear alkanes, alkenes, aromatic hydrocarbons, and monomer fragments (notably styrene in PS).
- *TGA/DTG*: Evaluated thermal degradation profiles with and without catalysts, confirming significant reductions in onset temperatures.

RESULTS

Thermogravimetric Analysis

The thermogravimetric analysis (TGA) results revealed some of the significant influence of both zinc oxide (ZnO) and copper oxide (CuO) catalysts at the thermal degradation behavior of the studied polymers. In the absence of catalysts, the polymers exhibited tremendously excessive onset degradation temperatures, with polyethylene (PE) and polypropylene (PP) beginning thermal decomposition at round 420°C and polystyrene (PS) at approximately 390°C. Upon the advent of the catalysts, there was a marked discount in these onset temperatures, indicating an enhancement in thermal degradation performance [10]. ZnO and CuO reduced the onset degradation temperatures by way of about 50 to one hundred°C depending on the polymer kind. This reduction of the thermal threshold can be attributed to the catalytic activity of the steel oxides, which facilitated the scission of polymer chains and promoted in advance decomposition.

In the case of PE and PP, the specific degradation process followed a single-stage decomposition pathway, in which the bulk of weight reduction happened inside a slender temperature range, usually between 350°C and 470°C below catalytic situations. This behavior is a function of random chain scission, superior by means of catalytic surfaces that decrease activation energy necessities. For PS, a -level degradation pattern becomes found, constant throughout both catalytic and non-catalytic runs [11]. The first stage involved the cleavage of facet chains and the release of risky monomeric fragments, at the same time as the second one degree was related to the breakdown of the polymer spine. Notably, catalytic presence shifted each degree to lower temperature zones and ended in a sharper mass loss profile within the DTG (Derivative Thermogravimetry) curves, indicating a more efficient and whole degradation manner.

The presence of the catalysts also caused a discount in residual solid mass after complete thermal treatment, further assisting their role in improving the decomposition kinetics and selling volatilization of deterioration merchandise. Among the 2 catalysts, ZnO consistently demonstrated barely extra catalytic pastime as inferred from the lower onset degradation temperatures and the higher weight reduction rate.

Product Yields

The analysis of product yields from the different degradation experiments demonstrated a clear dependence on both the type of catalyst used and the character of the polymer. The degradation technique led to three number one product streams: liquid hydrocarbons (oil fraction), non-condensable gases, and solid residue. Each of these fractions changed into measured quantitatively after the completion of pyrolytic runs beneath managed experimental conditions.

For LDPE degradation, ZnO facilitated the highest liquid yield, attaining as much as 78%, while CuO led to a slightly lower liquid yield of seventy two%. In evaluation, gas yields have been better for CuO at 22%, in comparison to 18% for ZnO, suggesting that CuO may also promote cracking reactions that want gaseous product formation. The stable residue was minimal in each instance, remaining underneath 6%. Similar traits had been observed for PP, where ZnO enabled a liquid yield of eighty one%, the very best among all samples tested. CuO became now not tested with PP in this section due to prioritization of resources for ZnO trials, however preceding studies have indicated comparable overall performance with a bent for extra gas technology.

In the case of PS, CuO brought about a liquid yield of 69% and a gasoline yield of 24%, once more highlighting its position in improving gas production. The higher fuel yield with CuO is indicative of secondary cracking reactions that convert heavier molecules into lighter, greater risky species. ZnO, with the aid of contrast, preferred the formation of longer-chain hydrocarbons and waxes, which have been extra regular inside the liquid section. This selectivity is probably related to the surface basicity and band gap differences between the 2 oxides, which affect catalytic pathways.

Overall, ZnO has proven advanced performance in maximizing the yield of liquid hydrocarbons, making it a greater suitable candidate for fuel-grade product healing. CuO, at the same time as slightly much less powerful in liquid yield, confirmed promise in applications geared toward gasoline-section strength healing or monomer recycling.

FTIR and GC-MS Analysis

The chemical composition and also the structural transformations occurring during the time of degradation process were mainly being investigated using Fourier Transform Infrared Spectroscopy (FTIR) and Gas Chromatography-Mass Spectrometry (GC-MS). FTIR analysis of the degraded polymer samples confirmed clean proof of polymer chain scission. In all instances, function peaks similar to C–H stretching (round 2900 cm^{-1}) and C–C stretching (round 1460 cm^{-1}) were drastically faded or absent in submit-degradation spectra, indicating the successful cleavage of these bonds. Additionally, new peaks emerged inside the regions associated with carbonyl and alkene companies, suggesting the formation of oxygenated and unsaturated compounds at some stage in degradation.

The GC-MS evaluation provided special insight into the nature of the degradation products in the liquid segment [12]. The chromatograms revealed a complex aggregate of alkanes, alkenes, cyclic hydrocarbons, and aromatic compounds. For PS, an extensive portion of the liquid section consisted of styrene monomers and derivatives, asserting the depolymerization nature of the reaction. For LDPE and PP, the presence of long-chain alkanes and alkenes turned dominant, especially in ZnO-catalyzed samples, indicating constrained over-cracking and true selectivity for fuel-like compounds.

One of the key observations throughout all samples and catalysts is the absence of halogenated or nitrogenated compounds, which are often related to environmental toxicity. This finding supports the environmental viability of the catalytic degradation process and underscores the advantage of the usage of steel oxides that don't sell the formation of risky by way-of-merchandise.

Catalyst Reusability

The reusability of catalysts is one of the main critical factors in determining the economic as well as operational feasibility of any form of catalytic degradation process. In this look at, both ZnO and CuO catalysts had been subjected to three consecutive degradation cycles to evaluate their balance and performance. After each cycle, the catalysts were recovered from the reaction residue, cleaned with ethanol and distilled water, dried at 110°C, and reused below the same experimental conditions.

The consequences demonstrated that each catalysts retained greater than eighty five% of their preliminary catalytic interest after three makes use of [13]. This becomes pondered in steady product yields, degradation temperatures, and product compositions throughout cycles. Structural analyses using XRD and SEM earlier than and after the degradation runs confirmed simplest minimal adjustments in crystal structure and surface morphology, indicating accurate thermal and chemical stability. BET surface place analysis confirmed that there has been no considerable pore crumble or sintering after multiple makes use of, mainly in the case of ZnO, which retained over ninety% of its preliminary floor region.

The slight decline in hobby located after the third cycle is in all likelihood as a result of surface fouling because of deposition of carbonaceous residues or minor sintering results [14]. However, those consequences were now not mentioned sufficient to compromise the overall performance of the catalyst. This locating affirms the potential of ZnO and CuO as sustainable catalysts for polymer waste degradation, with proper prospects for reuse in scaled-up operations.

Structural and Thermal Impact of Catalysts

Without catalysts, PE and PP degraded above 420°C. ZnO reduced onset to ~340°C, while CuO lowered it to ~360°C [15]. DTG showed sharper mass loss peaks with catalysts, indicative of efficient single-step or two-step scission pathways.

Liquid and Gas Yield Distribution

- *LDPE*: ZnO achieved a liquid yield of 78%, CuO ~72%.
- *PP*: ZnO yielded 81% liquid hydrocarbons.
- *PS*: CuO yielded 24% gas and 69% liquid, indicating deeper chain cracking and monomer depolymerization.

This suggests ZnO promotes β-scission and longer-chain hydrocarbon retention, while CuO enhances radical fragmentation and olefin formation.

Reaction Mechanisms and Functional Transformation

ZnO and CuO exhibit redox activity and surface oxygen vacancies that initiate free-radical chain scission. ZnO's amphoteric character stabilizes radical intermediates, favoring liquid product retention. CuO's p-type nature enhances dehydrogenation, producing short-chain volatile gases. FTIR confirmed disappearance of backbone bonds and formation of aldehydes and unsaturated groups [16].

DISCUSSION

Reaction Mechanism

The proposed mechanism involves the radical chain scission catalyzed by surface oxygen vacancies in ZnO and CuO. The presence of Lewis acid sites facilitates the breakdown of polymer chains:

- *ZnO*: Promotes β-scission, favoring liquid fuel production
- *CuO*: Enhances dehydrogenation and cracking, generating light gases

Comparison Between ZnO and CuO

ZnO gives higher hydrocarbon yield and thermal degradation efficiency because of its excessive bandgap and basicity. CuO, being a p-type semiconductor, favors the formation of olefins and aromatics [17].

Environmental and Economic Aspects

- Energy input is lower than traditional pyrolysis
- No toxic emissions detected

- Recyclable catalysts
- Potential for integration with municipal solid waste management structures

Catalyst Surface Stability and Reusability

After three cycles:

- ZnO retained ~90% surface area and catalytic activity.
- CuO retained ~85%, with minor fouling.

XRD and SEM showed no structural collapse or sintering. EDX confirmed elemental purity post-reaction, supporting long-term operational stability [18].

Surface and Interface Reactions in Composites

The catalytic interaction at the polymer–oxide interface mimics composite filler behavior. Embedding ZnO/CuO in polymer matrices pre-reaction could enable dual-functionality: degradation trigger and mechanical reinforcement in recyclable polymer composites.

Energy and Environmental Metrics

- Lowered degradation temperature reduces energy input by 20–30% over conventional pyrolysis.
- No halogenated or toxic by-products were detected via GC-MS.
- Catalysts are recyclable with no hazardous leaching, aligning with green catalyst design principles.

Potential for Integrated Recycling Systems

The process can be adapted to:

- Municipal solid waste-to-fuel recovery [19].
- Inline degradation units in polymer processing plants.
- Closed-loop systems for fuel, monomer, and composite precursor recovery.

CONCLUSION

This study confirms the capacity of ZnO and CuO as powerful catalysts for polymer degradation. ZnO suggests better selectivity in the direction of liquid hydrocarbons, even as CuO complements gas yield. Both catalysts offer energy-green, scalable, and environmentally friendly options for plastic waste management.

Key Findings

- ZnO and CuO lower the degradation temperature by up to 100°C
- Over 75% conversion of polymers into various useful hydrocarbons [20]
- Minimal catalyst degradation after multiple uses
- Environmentally benign process

Recommendations

- Scaling up to pilot-scale reactors
- Exploring bimetallic oxide systems
- Life cycle assessment (LCA) of the process
- Integration with renewable energy inputs

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