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Advances and Emerging Trends in Green Chemistry: A Comprehensive Review

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Abstract: ***Green Chemistry has emerged as a transformative approach within chemical sciences, emphasizing the design of environmentally benign materials, safer processes, and sustainable industrial technologies. Unlike traditional chemistry that manages pollution post-formation, Green Chemistry focuses on preventing the creation of hazardous substances at the molecular level. This review explores major advancements in green solvents, catalytic technologies, renewable feedstocks, and energy-efficient synthetic methodologies. Special emphasis is placed on the increasing industrial applications in pharmaceuticals, agriculture, polymer science, and clean energy sectors. The discussion also highlights current global challenges and future opportunities associated with sustainable chemistry. The review concludes that Green Chemistry now plays a crucial role in shaping eco-friendly manufacturing and offers promising prospects for achieving long-term environmental sustainability.***

Keywords: Green Chemistry, Catalysis, Sustainable Technology, Renewable Feedstocks, Green Solvents, Environmental Safety, Pollution Prevention.

I. INTRODUCTION

As global awareness about environmental degradation grows, industries and researchers are shifting focus from pollution control to pollution prevention. Green Chemistry, often referred to as sustainable chemistry, aims to address environmental problems by adopting safer synthetic pathways, reducing hazardous waste, and designing degradable chemical products.

The field is built upon 12 fundamental principles that collectively redefine chemical design, energy usage, solvent selection, feedstock choice, and waste management. Green Chemistry is not only a theoretical framework but a practical guideline for developing sustainable industrial practices. The increasing demand for eco-friendly products, strict global regulations, and the need for resource conservation have made Green Chemistry an essential part of modern scientific development.

This review explores historical development, theoretical foundations, technological advancements, industrial integration, and future opportunities within Green Chemistry.

II. PRINCIPLES OF GREEN CHEMISTRY

The 12 principles of Green Chemistry establish a scientific foundation for designing safer products and environmentally responsible processes. These principles include: Prevention of waste, atom economy, less hazardous synthesis, designing safer chemicals, safer solvents, energy efficiency, renewable feedstocks, reduced derivatives, catalysis, design for degradation, real-time pollution analysis, and accident prevention.

III. RECENT ADVANCES IN GREEN CHEMISTRY

A. Green Solvent Technologies

Supercritical CO_2, water-based reactions, ionic liquids, and deep eutectic solvents are major advances that reduce toxicity and improve safety.

B. Renewable Feedstocks

Cellulose, lignin derivatives, biomass-based platform chemicals like HMF, and vegetable oils have replaced petroleum feedstocks in many applications.

C. Catalysis in Sustainable Chemistry

Enzymatic catalysis, nano-catalysts, photocatalysis, and heterogeneous catalysts have transformed reaction efficiency and environmental safety.

D. Energy-Efficient Synthetic Techniques

Microwave synthesis, ultrasonic chemistry, flow chemistry, and mechanochemistry significantly reduce energy consumption and waste generation.

IV. INDUSTRIAL APPLICATIONS OF GREEN CHEMISTRY

1) Pharmaceutical Sector: Greener solvents, enzyme-mediated drug synthesis, continuous-flow reactors, and reduced hazardous by-products.
2) Agriculture: Biodegradable pesticides, nano-fertilizers, and controlled-release formulations that reduce environmental contamination.
3) Polymer and Material Science: Biodegradable plastics, CO_2-based polycarbonates, recyclable polymers, and bio-composites.
4) Green Energy and Environmental Remediation: Photocatalytic hydrogen, organic solar cells, eco-friendly batteries, and catalytic pollutant degradation.

V. CONCLUSION

Green Chemistry has become a fundamental necessity in addressing global environmental challenges. Its principles encourage the development of safer, cleaner, and more sustainable technologies across industrial sectors. Recent advances in catalysis, renewable feedstocks, and energy-efficient synthesis have accelerated progress toward pollution-free chemical manufacturing. As industries increasingly adopt green technologies, the future promises innovative solutions combining economic viability with environmental responsibility.

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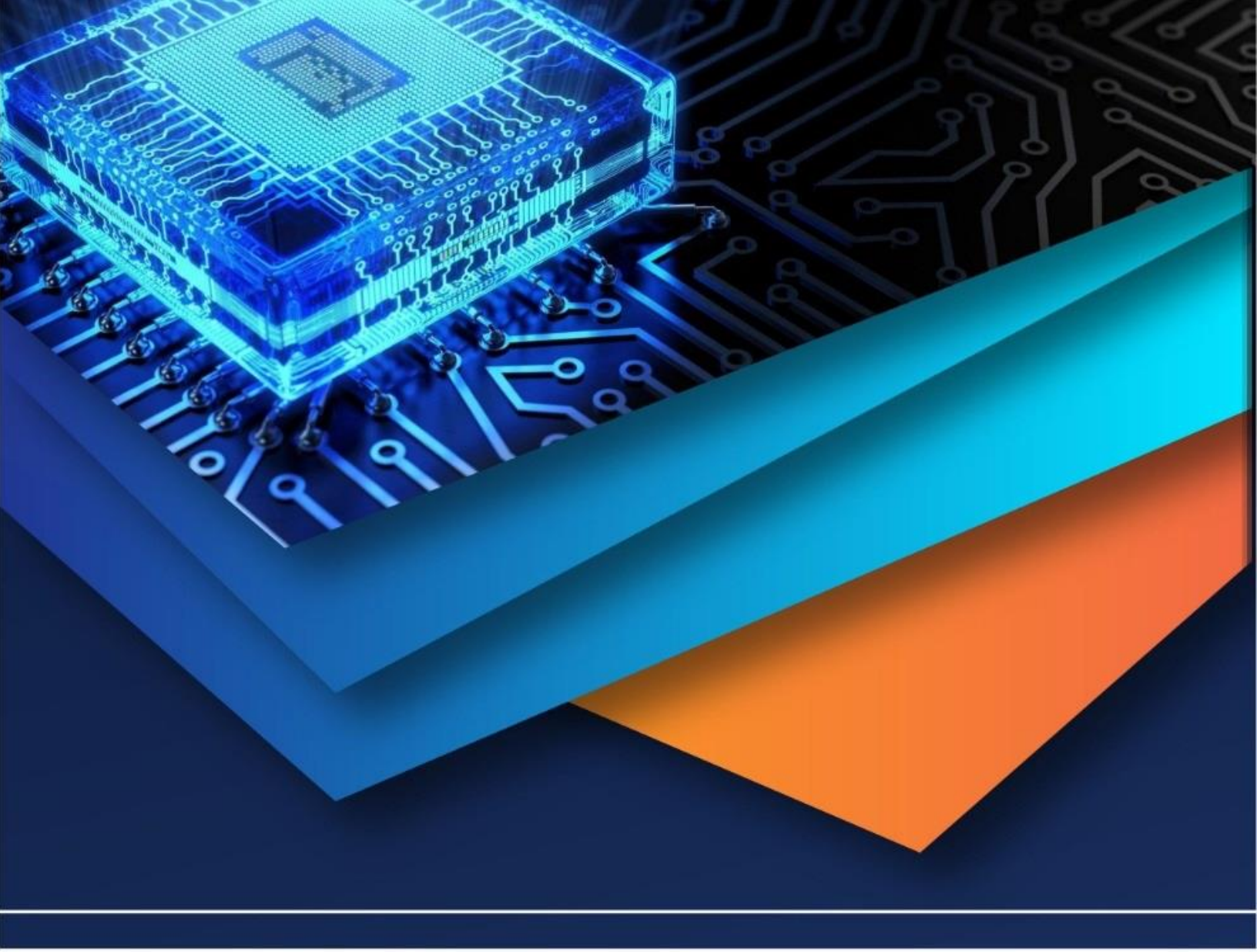

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