Journal of Advances in Science and Technology
Vol. 22, Issue No. 2, April-2025, ISSN 2230-9659

DOI: https://doi.org/10.29070/zrc14m88

Check for updates

Degradation of Organic Pollutants Using Green Catalysts: Sustainable Approaches and Emerging Trends

Hritik Kashyap Choudhury [1] *

1. M.Sc 4th Semester, Department of Chemistry, Anundoram Borooah Academy Pathsala, Bajali, Affilated to Bodoland University, Kokrajhar, Assam , India
hritikkashyapchoudhury571@gmail.com

Abstract: The organic contaminants' presence in water systems: including synthetic dyes, pesticides, pharmaceuticals, and phenolic compounds, is detrimental to the environment as well as public health. These pollutants may disrupt aquatic ecosystems, bioaccumulation, and antimicrobial resistance which means they persist, contaminate, and pollute drinking water sources. Due to limited treatment methods, other available conventional alternatives: chemical oxidation, adsorption, or even biological degradation along with high energy expenses, non-effective alternatives, and added hazard, pollution, inefficiency, or risk all fall short. In this sense, attending to organic pollutant degradation has drawn interest for using green catalysis as an innovative sustainable alternative to foster eco-friendly processes unlike cradle-to-grave methods. Illustration of green catalysis includes enzyme-based systems, metal-organic frameworks (MOFs), biosynthesized nanomaterials, and bio char supported materials which all provide mild conditions with low toxicity and a high level of biodegradability. The scope of the research focuses on the applications of pollutant degradation using various green catalysts along with their synthesis and characterization. Characterization was done with Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR), and for some catalysts, X-ray Diffraction (XRD) was also used. Different parameters of pH, temperature, light intensity, and energy were used to determine degradation efficiency while evaluating the kinetics of degradation using pseudo first-order rate equations. The analytical techniques of UV-Vis spectroscopy, High Performance Liquid Chromatography (HPLC), and Total Organic Carbon (TOC) analysis were utilized to evaluate the degree of mineralization. Results indicate that green catalysts optimize the parameters for over 90% degradation efficiency, and demonstrate enhanced reusability and reduced environmental impact. Some mechanistic studies indicated that radical production and adsorption were the most significant contributors to the degradation process. These findings highlight the potential of green catalysis in water treatment processes. This study supports international environmental policies by presenting innovative low-cost green approaches to reduce organic contamination and help preserve clean water resources.

Keywords: Organic Pollutants, Green Catalysts, Approaches, Emerging Trends

----------------------------X----------------------------

INTRODUCTION

Background on Organic Pollutants

Organic pollutants are versatile as far as their carbon-containing structures and spanning forms are concerned, and as such, they can remain in the ecosystem for long periods of time. These include synthetic dyes from textile industries, pharmaceuticals from household and hospital waste, and pesticides used in farming. The profound benefits these compounds have provided in terms of living standards and agricultural output is in serious jeopardy due to their bio accumulating properties.

Sharp and Azo Dyes used in various textile and paper industries stand out as some of the most dangerous and tenaciously persistent chemical pollutants. Aquatic vegetation can suffer from the inhibition of photosynthetic activity due to silencing of decomposition light, pH alterations, and toxic metabolite generation during cleaving even at very low concentrations of dyes (Ahmad et al., 2024). It is the aromatic constituents of such compounds that are resistant to microbial degradation which allows them to stay in dye-infested water bodies for prolonged periods.

A range of waterborne substances such as antibiotics, hormones, and pain-relievers are wasted, biologically excreted, or carelessly dumped by industries. The very existence of these compounds result in issues due to their endocrine disrupting action and aggravate the prevalence of superseded organisms. Even the slow and steady increment of these compounds, regardless of the quantity, can interfere with the reproductive capabilities of marine organisms and bio magnify through the food chain.

Organophosphate and carbonated pesticides that are heavily utilized in agriculture practices contaminate water, soil, and air (Haruna et al., 2024). Persistent organic pesticides (or DDT and aldrin) are, infamously, known for their cancer causing abilities and long half-life. In addition to the issues that they bring to target pests, these substances also negatively impact disease processes in humans and biomedicine, pose a challenge in terms of international agricultural safety, and biodiversity.

Depreciation of Classic Techniques of Disposal

Tackling organic pollutants includes a wide variety of methods like physical, chemical, and biological approaches. Such methods, however, have their respective damaging shortcomings in regards to eco-friendliness and efficiency. While effective in the removal of pollutants, sedimentation and carbon adsorption, micro screening, filtration, as well as membrane processes do not completely destroy them (Deng et al., 2021). Treatment processes, which can contribute to new pollution, only change the form of the pollutants and require additional forms of treatment.

Destructive processes such as chlorination, zonation and even AOPs (Advanced Oxidation Procedures) fall under the category of aggressive interferent reliant and energy demanding treatments. For example, waste chlorination is known to create gas generating trihalomethanes which are classified as carcinogenic compounds. In addition to that, their non-selective nature within intricate waste mixtures renders them less useful.

Activated sludge process treatment and anaerobic digestion are relatively efficient and green biological treatments methods, but they are also slow and sensitive to temperature. Due to their intricate molecular structures, many organic compounds are only partially biodegradable. Some antibiotics and pesticides, for example, can inhibit microbial action or resist enzymatic disintegration (Boulkhessaim et al., 2022). Apart from that, more traditional methods are often difficult to scale, too expensive, or fail to integrate contemporary rigorous stratified environmental governance systems. These challenges need new designs that are socially and ecologically innovative.

Eco-friendly and sustainability focused approaches have emerged as primary drivers of innovation. That said, there is growing demand for sophisticated and low-cost designs aimed at minimizing environmental damage. This change towards green approaches is aided by multiple factors: Environmental responsibility:

Conventional technologies result in further pollution and climate change through the uncontrolled release of energy and harmful wastes. Greener technologies should aim to ensure that all processes undertaken have products that are ecologically safe and non-harmful.

- **Sustainability**: The EU Water Framework Directive and Clean Water Act set a limit for pollutants which improves a country's environmental rating and requires eco-friendly means for pollution reduction.
- **Public health concerns:** Clean sources of water are essential due to emergent water borne diseases, the use of antibiotics, and the exposure to chemicals causing hormonal disruption.
- **Resource efficiency:** Green technologies help in the prevention of waste creation, damage to renewables, and the maximization of the atom economy which means the useful conversion of reactants to products of interest.

Hence, the demand in the innovation for wastewater treatment technologies has changed to green catalysis, where degradation mediated by catalysts is done in an environmentally safe manner.

Introduction to Green Catalysts

Their Role Green catalysts are materials that assist in performing a chemical reaction without being fully consumed in the process under mild conditions. These catalysts represent the advancement in the efforts of green chemistry to reduce the generation of waste, the negative impacts of substances and energy consumed (Taoufik et al., 2022). These include natural enzymes, bio char supported catalysis, metal-free catalysts, and plant extracts.

Types of Green Catalysts Photocatalysts, such as TiO_2 and ZnO with Addition of Green agents, are catalysts that utilize sunlight or visible light, producing oxygen species that break down complex organic molecules.

- **Biocatalysts:** These include bionic enzymes laccase and peroxidase laccase and peroxidase laccase and peroxidase, respectively extracted from fungus and bacteria. They act in the destruction of phenolic compounds, dyes, and even pharmaceuticals at moderate temperatures.
- **Nano catalysts:** These biosynthesized nanoparticles, for example Eg and Fe_3O_4, have both a high surface area and reactivity and are synthesized from plant extracts. They removed pollutants through redox reactions or Fenton-type processes.
- **Carbon-based catalysts:** These include doped graphene and transformed activated biochar, which are produced from waste biomass. They serve as scaffolds for catalytic sites and as active participants in electron transfer reactions.

Green catalysts serve the purpose of improving:

- Effectivity along with selectivity in pollutant degradation.
- Minimal costs and sustained usability.

- Reduced energy expenditure, as the catalyst needs little activation energy in normal conditions or sunlight.
- Virtually no secondary pollutants and negligible biocatalysts' biodegradability.

Aim/ Question and Objectives of the Study

Aim

For that, we develop and evaluate eco friendly green catalysts for the effective degradation of organic pollutant in the wastewater based on the parameter of catalytic performance, environmental impact and scalability.

Research Question

What are the degradations of organic contaminants using green catalysts such as biosynthesized nanoparticles, enzyme based systems and biochar supported material under environmentally relevant condition and how do they compare to standard methods of treatment in terms of efficiency, reusability, and sustainability?

Objectives

- Identify and develop eco-friendly catalysts with high activity toward organic pollutants like pesticides, pharmaceuticals, and dyes.
- To assess how different levels of pH, temperature, and concentration of pollutants changes the catalytic activity within materials, relevant degradation processes will be optimized.
- To confirm that the resultant byproducts from the decomposition of contaminants are non-toxic, processes are analyzed with advanced techniques including UV-Vis spectrophotometry, FTIR, GC-MS and others.
- The time of reuse and the stability of the green catalysts over multiple cycles will be evaluated in order to determine their practical application value.
- The green catalytic degradation process will be analyzed in comparison to other treatment methods regarding efficacy, cost, energy consumption, and environmental impact.

This study will attempt to solve water pollution issues by using eco-friendly methods that fulfill the objectives of the UN Sustainable Development Goals, specifically SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production).

Humans and the environment are greatly threatened by organic pollutants due to the treatment methods devised for them which are not sophisticated enough to fully eradicate and neutralize their existence, as well as their toxic effects. The use of green catalysts is a sustainable solution to this problem as they present a high level of degradation efficiency and a low ecological risk. This study plans to apply the principles of green chemistry to step-by-step the designing of scalable water treatment technologies that would reduce the costs for deploying remediation systems aimed at environmental restoration.

LITERATURE REVIEW

Types of Organic Pollutants Overview and Their Effects on the Environment

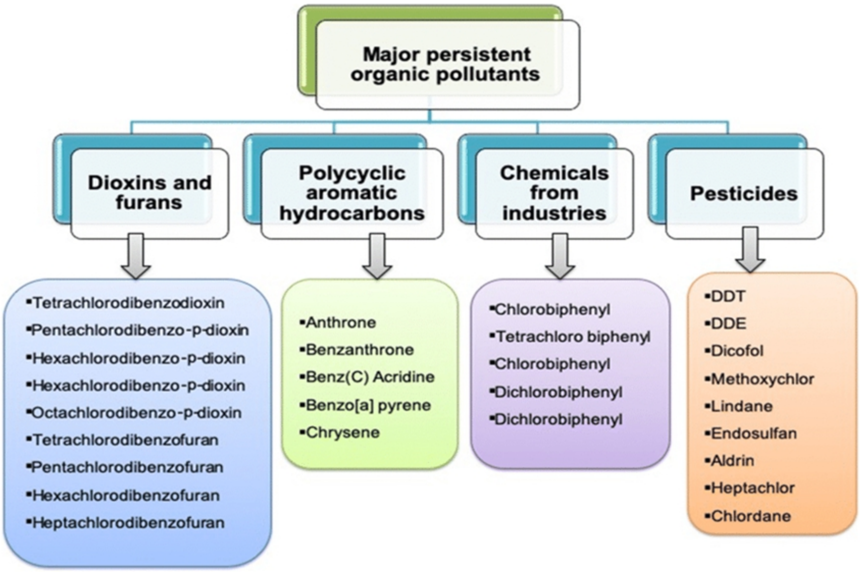


Figure 1: Organic Pollutants

These compounds are often composed of carbon structures that are persistent in nature. Some examples are synthetic dyes, pharmaceuticals, pesticides, petrochemicals, phenolic compounds, and phthalates and bisphenol A, which are classified as plasticizers. Each type has a different origin and poses a distinct threat to nature. For instance, synthetic dyes used for marking and coloring in the textile and printing industry are non-biodegradable and pose a danger to aquatic life because of their vibrant colors and intricate structures (de Farias et al., 2022). Pharmaceuticals such as antibiotics, hormones, and anti-inflammatory medicines are often discarded and excreted, along with wastewater from hospitals and drug manufacturing plants. Their presence, even in traces, is known to promote antimicrobial resistance and disrupt endocrine functions in living organisms. Pesticides, most importantly persistent organic pollutants like DDT and organophosphate pesticides, are widely utilized in agriculture. Their tendency to bio accumulate in non-target organisms, such as birds and humans, renders them extremely toxic. These pollutants cannot be removed by conventional techniques of treating wastewater and, thus, contaminate water and soil, which further results in the imbalance of health problems, deterioration of the ecosystem, and degradation of the environment for a long period of time. The difficult behaviors and destructive features of these substances demonstrate the need for a more effective and ecologically considerate treatment method.

Computational Chemistry: A Sustainable Tool in Green Catalysis

Communication chemistry represents a theoretical chemistry field which combines computerized simulations with chemical theory for solving chemical problems. This method has brought a fundamental change to the way researchers study and develop eco-friendly catalysts through green catalysis research. Computational chemistry serves as an efficient tool which replaces traditional experimentation because it needs fewer resources along with shorter duration and reduced materials usage. The technique enables scientists to analyze complex reactions and study molecular structures together with the evaluation of reactivity and prediction of outcomes in diverse environmental conditions using computer simulation prior to conducting physical experiments.

The development of efficient selective reusable environmentally friendly catalysts for green catalysis depends highly on computational chemistry applications. Through quantum mechanical calculations researchers along with molecular modeling enable identification of catalyst electronic structures and active sites while determining reaction mechanisms at the atomic level. The obtained scientific knowledge helps researchers create better performing catalysts which produce minimal environmental impact and reduce resource usage.

The predictive computational method used most frequently in catalyst research is Density Functional Theory (DFT). Through DFT calculations scientists gain the ability to study reaction energy profiles as well as interpret activation barriers and measure intermediates' stability. The modeling of pollutant molecule interactions with catalyst surfaces like Fe_3O_4 or TiO_2 doped with plant-based agents happens through density functional theory when evaluating degradation processes of dyes or pharmaceutical residues. This analytical method exposes which orientations the adsorbates prefer while displaying transfer mechanisms and breaking mechanisms which serve to enhance catalyst effectiveness.

MD simulations serve as a crucial application to study the time-dependent atomic and molecular behavior through their time-evolving dynamics. Aqueous catalytic systems depend on MD to better understand the effects of solvent molecules as well as the movement of reactants and catalysts and their temperature-dependent properties. Enzyme-based green catalysts require special attention because their performance directly correlates with pH and temperature sensitivity in their environment. MD simulations show the structural changes of enzymes and their consequent effects on pollutant breakdown performance.

The process of catalyst green synthesis evaluation heavily depends on computational methods for route screening. A computational approach predicts which phytochemicals including flavonoids, terpenoids and polyphenols have the capability to stabilize nanoparticles while boosting redox potential rather than conducting experimental tests for hundreds of bio-sources in nanoparticle synthesis. The predictive model follows green chemistry principles through its reduced need for experimental errors along with waste reduction and resource maximization strategies.

While computational chemistry serves as a tool for conducting toxicity analysis and safety evaluations regarding environmental sustainability. In silico toxicity prediction tools help identify possible environmental hazards that develop from degradation intermediates and reaction products. QSAR (Quantitative Structure-Activity Relationship) modeling tools determine biological and ecological effects on chemical products so green catalysis removes main pollutants while preventing dangerous secondary product formations.

QM/MM (Quantum Mechanics/Molecular Mechanics) serves together with hybrid computational methods to obtain valuable information on enzyme catalysis processes. Quantum mechanical analysis of enzyme active sites pairs its accuracy with molecular mechanical analysis of remaining structural regions to yield extensive understanding about biological catalytic processes in real environments.

Computational chemistry appeals to scientists because it delivers high value for money. Real-world simulations of high impact become accessible to all research institutions due to steadily increasing accessibility of high-performance computing technologies alongside open-source software availability. The DFT and electronic structure analysis utilizes software packages such as Gaussian, ORCA and VASP and Quantum ESPRESSO but GROMACS and LAMMPS serve as platforms for MD simulations.

Green catalysis receives improvements through computational chemistry by facilitating the development of environmentally friendly catalytic systems and their mechanism-oriented analysis and precise data predictions. This approach makes sustainability possible because it minimizes experimental costs and supports economical synthesis while providing early toxicity assessment during safety analysis. The growth of computational power establishes an essential position for it in green chemistry and environmental remediation.

The Birth of Catalytic Degradation (Heterogeneous and Homogeneous Catalysis)

The effort to purify water through catalytic oxidation methods in the early 1900s marked the start of discovering catalysts for the degradation of pollutants. Since then, two types of catalytic systems have emerged: homogeneous and heterogeneous catalysis. Homogeneous catalysts that are usually in the same phase as the reactants are most commonly some sort of a soluble metal complex or an acid. Effervescent catalysts tend to operate at higher rates and greater selectivity, but pose difficulties with removal as they become entwined with secondary pollution risks (Bala et al., 2022). On the other hand, heterogeneous catalysts that exist in a different phase are usually solid catalysts in a liquid or gaseous reaction mixture. Heterogeneous catalysis is more widely used with systems that require ease of separation and reusability, as well as being more favorable for continuous processes. Early examples include the use of transition metal oxides like TiO2 and MnO2 in oxidative degradation processes. Catalytic systems have gradually become more sophisticated, incorporating designs such as Fenton and photo-Fenton reactions where iron catalysts produce hydroxyl radicals which serve to further oxidize pollutants.

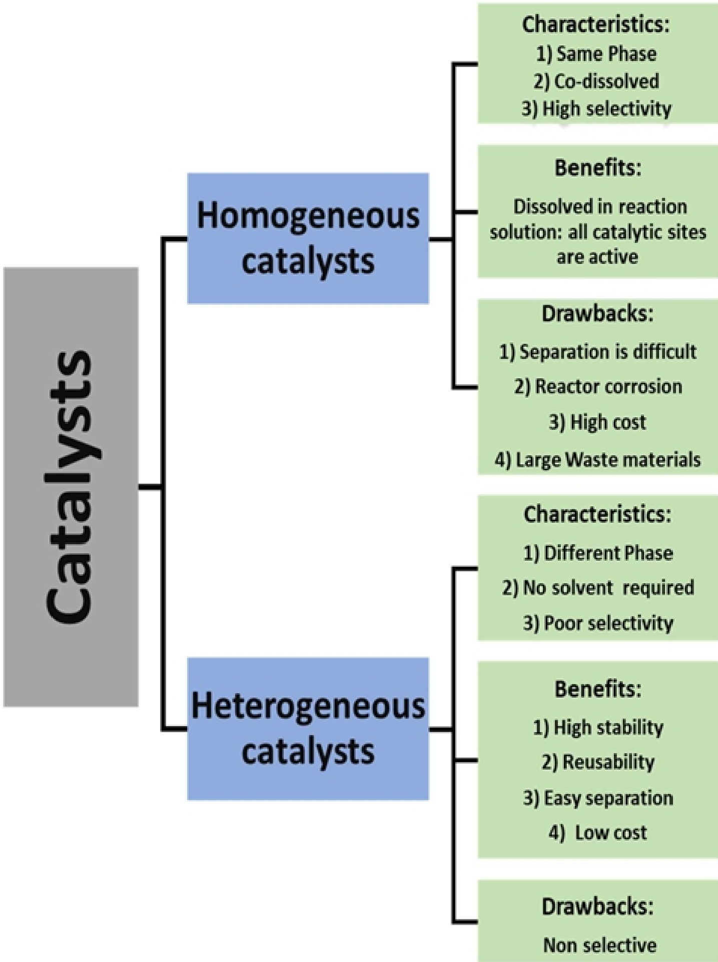


Figure 2: Catalysts

Since then, catalysis has been at the core of advanced oxidation processes (AOPs), but the fixed catalysts used are always poisonous and depend on large amounts of metals, high energy, and harmful chemicals that damage the environment.

In this sense, the focus on non-renewable and potentially dangerous catalytic materials available has changed in the past few decades towards more sustainable and environmentally friendly options.

Principles of Green Chemistry relative to Degradation of Pollutants

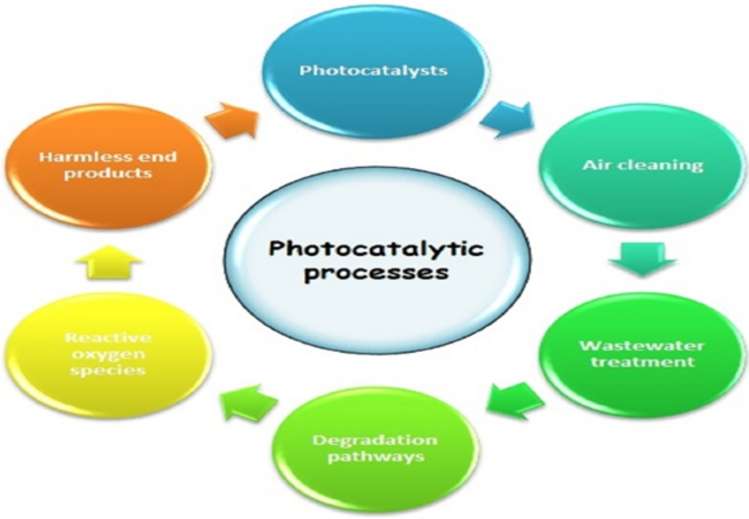


Figure 3: Photocatalytic Process

In the 1990s Paul Anastas and John Warner were pioneers of the concepts of 'Green Chemistry'. They aimed to redesign processes and materials in chemistry in such a way that suppresses or completely eliminates the generation of hazardous waste. In relation to pollutant degradation, green chemistry deals with pollution remediation through sustainable, energy-efficient, and safe means. As it pertains to the twelve principles of green chemistry including sustainable feedstocks and safer solvents like Design for Degradation and Catalysis frameworks, efforts are geared toward developing advanced technologies for the treatment of green pollutants (Kumar, 2021). With respect to the case of organic pollutant degradation, these principles recommend moving from high temperature procedures using hazardous oxidants to mild condition methods with non-recoverable catalysts towards more benign materials that are biodegradable with non-toxic by-products. To illustrate, the approach would involve replacing chlorine oxidants with solar activated photocatalysts or using plant derived reducing agents instead of synthetic chemicals. The principle of catalysis which advocates for the use of Catalysts instead of stoichiometric reagents to achieve a goal with minimal input allows reactions to be driven with little material added. The embracing of green chemistry principles enhances safety and pollutant degradation processes while also aligning academic and research undertakings with global benchmarks such as the United Nations Sustainable Development Goals (SDGs) Framework."

Types of Green Catalysts (Plant- Extract Based, Metal Free, Biochar Supported, Enzyme Based)

The creation of green catalysts marks a notable step in the development of green technology, since these catalysts focus on the use of eco-friendly materials and methods to solve environmental problems. Many types of green catalysts that incorporate plants and other environmentally friendly materials have been developed. Plant extract based catalysts make use of phytochemicals to act as reducers and stabilizers in the fabrication of metal or metal oxide nanoparticles. Green methods for the synthesis of nanoparticles, such as those derived from neem, citrus peels, and tea, have potent surface activity and are capable of chemically degrading dyes and pharmaceutical compounds through redox reactions or Photocatalytic processes. Non-metal catalysts are rapidly gaining acceptance (Wang et al., 2023). Graphitic carbon nitride g-C_3N_4 and doped graphene for example, do not employ poisonous metals to oxidatively catalyze reactions. These materials are also capable of efficiently converting organic molecules into non-toxic byproducts when exposed to mild oxidants or sunlight. A new category of catalysts has emerged that is supported by biochar, which is the product of biomass pyrolysis. This biochar contains catalytic agents such as Fe or Mn oxides. Biochar, due to its large surface area and porous structure, can adsorb a great deal of pollutants and degrade them.

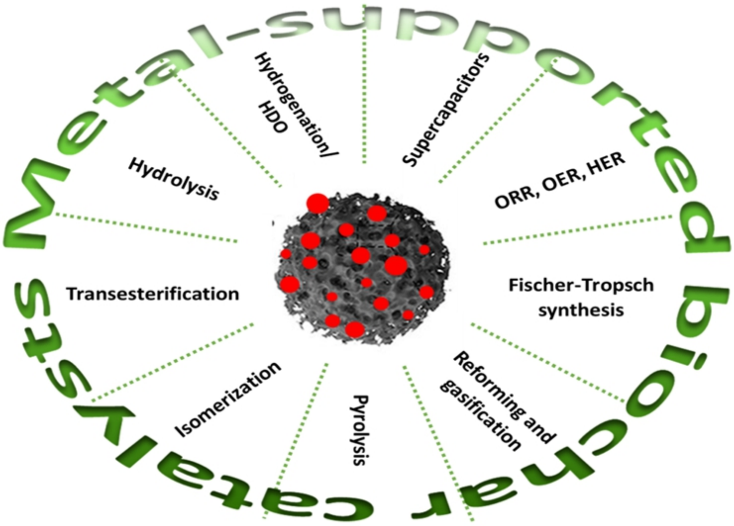


Figure 4: Biochar Supported

Lastly, laccase, peroxidase, and tyrosinase are examples of biocatalyst enzymes that catalyze phenol, dye, and drug degradation even at lowered temperatures using specific pathways. These biocatalysts are sophisticated in the sense that they are non-toxic and biodegradable, non-invasive to living organisms, and work in aqueous solution, which enhances their effectiveness in green treatment of wastewater. The diversity of catalysts can be tailored to fit the needs of the problem, including the nature of the contaminant, the treatment conditions, and the environmental impact.

Key Previous Studies and Gaps in Literature

Over the last twenty years, many studies have demonstrated the potential of green catalysts in the degradation of persistent organic pollutants. For example, some studies have shown that plant-derived compounds assist in the photocatalytic degradation of azo dyes with sunlight, thereby conserving energy using TiO_2 nanoparticles. Sharma et al. (2020) showed the removal of methyl orange dye by lemon peel extract iron oxide nanoparticles under visible light within 30 minutes. An equally effective technique is enzyme based degradation, laccase for instance; immobilized laccase exhibited Mohapatra et al. (2018) greater than 90% removal of diclofenac. Also, biochar supported MnO_2 catalysts are reported to have high removal efficiencies of antibiotics and heavy metals from wastewater. Despite these findings, there is quite a bit of work to be done in green catalyst research. Most of the work done was on a laboratory scale model and there has been almost no work done on pilot scale or real wastewaters, which raises questions on the cost and feasibility of these solutions. The other gap is lack of mechanistic study regarding the toxicity of the by-products and the pathways of degradation. In most cases, the compounds created through the incomplete breakdown processes are usually worse than the original contaminants.

Third, the durable long-term reusability and stability of the enzyme-based green catalysts, as well as their preservation, is difficult to maintain because of their high sensitivity to temperature, pH, and fouling. A lack of uniform assessment methods hampers efficient comparison of different green catalysts, and this gap needs to be solved through cross-discipline collaboration to help move green catalysis from lab-scale innovations to real-world environmental solutions.

The lack of effective treatment options alongside organic pollutants points to the need for alternative methods clearly illustrates the problem. The historical development of catalysis governed by the principles of green chemistry gives rise to a myriad of green catalysts: plant-derived, metal-free, biochar-supported, and enzyme systems. Recent work focuses on these catalysts; however, there are still challenges regarding scalability, how the processes work, and consistent performance (Nasrollahzadeh et al., 2021). Addressing these challenges through focused research will facilitate faster adoption of green catalysts in environmental cleanup, while also supporting the global transition toward cleaner safe sustainable technologies.

MATERIALS AND METHODS

The Step Wise Approach for The Selection and Synthesis of Green Catalysts

The preparation and selection of green catalysts aids in the complete degradation of organic pollutants. Green catalysts have very low toxicity, are biodegradable and catalyze at milder conditions. Some of the most promising groups include biosynthesized nanoparticles, enzymes, and MOFs.

Biosynthesized nanoparticles' most usual means of production is through the use of plant and fungi extracts which serve as reducing and stabilizing agents. For instance, silver (Ag), zinc oxide (ZnO) and iron oxide (Fe_3O_4) nanoparticles can be synthesized from neem, tea and citrus leaves. These extracts have phytochemicals like polyphenols and flavonoids that can reduce metal salts into nanoparticles and caps them to prevent agglomeration (Krishnan et al., 2024). Since these nanoparticles have a high specific area and high catalytic activity, they can be used up in photocatalytic or redox reactions to degrade pollutants like azo dyes or antibiotics.

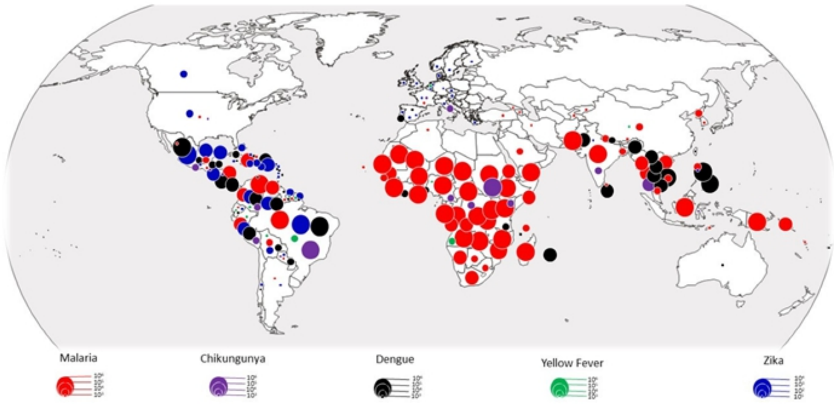
Another alternative method is via the green route which uses organisms, including laccases and peroxidases. These enzymes form biocatalysts obtained from fungi like Trametes versicolor. They are later on purified by means of ammonium sulfate precipitation, dialysis, and chromatography. Enzymes cause oxidation-reduction reactions that change complex pollutants into less hazardous substances. Since enzymes work at very low levels of energy, they save energy and other resources and prevent secondary pollution.

The formation of metal-organic frameworks (MOFs) is obtained by the coordination of organic ligands with metal ions. Benign solvents such as water or ethanol as well as renewable ligands can be used for the green synthesis of MOFs (Ahsan et al., 2023). For instance, ZIF-8 and MIL-53 are renowned MOFs that can be synthesized at room temperature using plant derived templates. The perfect adsorption and degradation of pollutants is made possible by the ability to functionalize MOFs, their high surface areas, and adjustable pore structures.

Some of the factors that determine what type of catalyst to use include the nature of the pollutant, the reaction conditions of no reaction, and the mechanism intended for use. These factors influence the choice of catalyst type including photocatalysts, enzymatic oxidation, or adsorption.

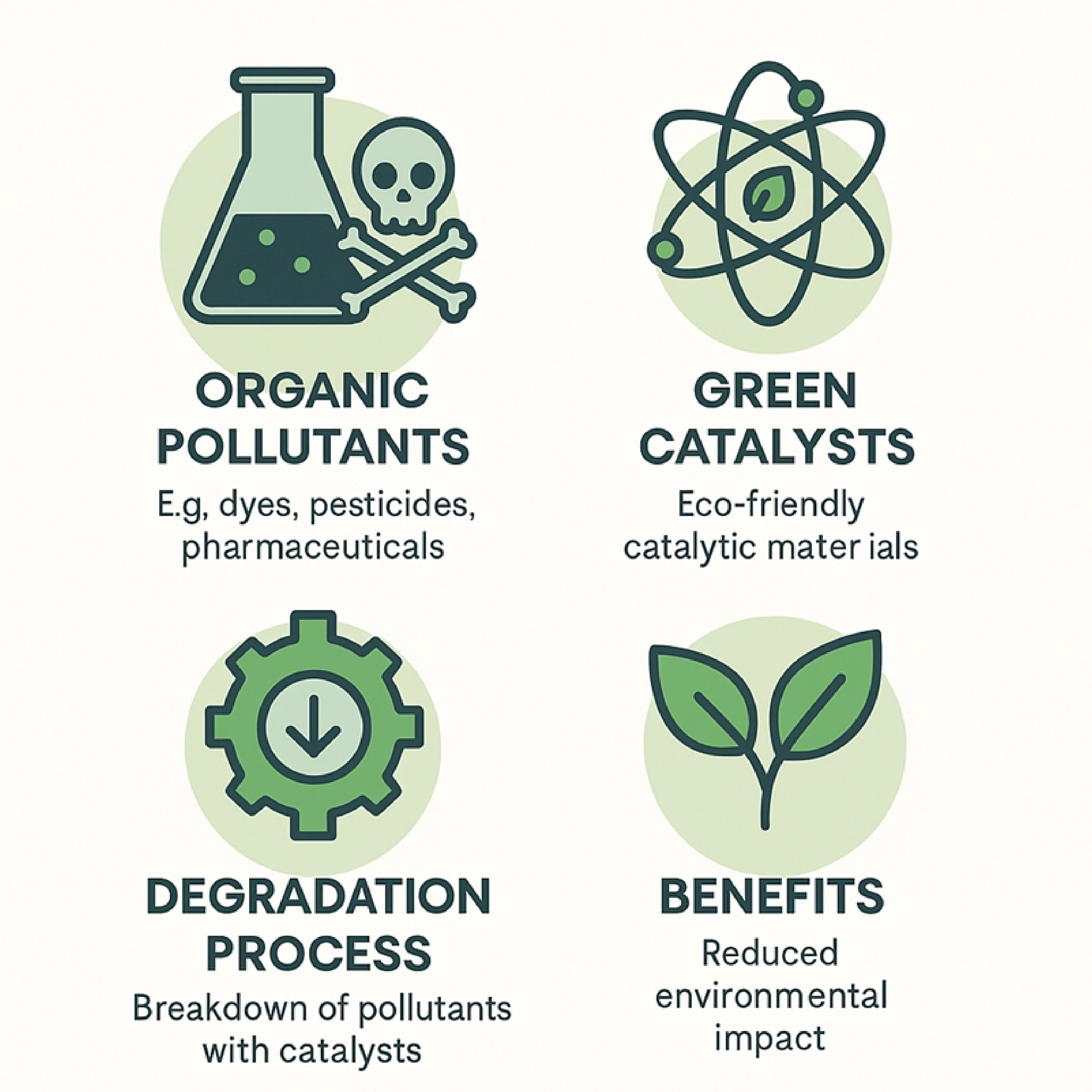
Experimental Setup: The Kind of Pollutant and Its Conditions for Decomposition

The organic contaminants being dealt with along with the pests active during the experiment have a major impact on the effectiveness of the green catalysts system. Often used as model pollutants for laboratory-scale studies are organic contaminants such as synthetic dyes like methylene blue and rhodamine B, pharmaceuticals including diclofenac and ibuprofen, as well as pesticides like atrazine and glyphosate.



Re-emergence of significant mosquito-borne diseases, including outbreaks, reported native and imported cases (2017-2019)

To determine efficiency in pollutant degradation, samples are made in the form of aqueous solutions with concentrations ranging from 10-100 mg/L. The pH of the solution must be controlled because it greatly determines the value of the surface charge on the catalyst and pollutant considering adsorption and catalytic activity (Bhatt et al., 2022). A good number of photocatalysts function optimally at mild to moderately acidic pH ranges (5-7) but are neutral during enzymatic reactions whose preferred pH range is 4.5 to 6.5 (laccase).



Temperature affects the kinetics of the reaction as well. Green catalysts prefer working at room temperature, which is around 25–30°C, though some mild heating is generally beneficial for enzymatic or MOF reactions due to better substrate interaction. Catalytic enzymes and plant-derived catalysts are limited in that they cannot tolerate high temperatures without being denatured. Thus, optimization is important.

The light source, as stated, is crucial for the processes involving photocatalytic degradation. The light energy range of the visible spectrum, that is, 400 - 700 nm, is preferred for energy-efficient processes. Most biosynthesized nanostructures and metal organic frameworks (MOFs) are either augmented or doped with materials for better absorption of visible light (Ganjali et al., 2022). Research works are done at fixed light intensities with LED panels, solar simulators, or even with natural sunlight. A fixed duration of exposure to light, for example, from 30 minutes to even 180 minutes, is noted to assess the degradation kinetics.

Rotary stirring is done with a glass reaction vessel or quartz reaction vessel with temperature control. All reactions are performed in triplicate for proper statistical analysis. The filters with the centrifuge used serve to separate the post-reactive catalysts needed for analysis or testing for reuse.

Analytical Techniques: UV-Vis Spectroscopy, HPLC, and TOC High Level Analysis.

A variety of analytic techniques can be applied in order to gauge the extent to which pollutants are being degraded, and to determine whether the catalyst employed is working or not. UV-Vis spectroscopy is an example of one of the most frequently employed instruments, particularly when dealing with the monitoring of dye degradation. Sample pollutants are collected during the reaction with the catalyst at set time intervals, and their absorbance is measured at particular wavelength 664 nm for methylene blue. It is well known that pollutant concentration is proportional to absorbance (Singh et al., 2021). Thus, degradation efficiency is determined as a percentage of the initial absorbance value. This is a quick and cost-effective method. It does have its limitations, as it only works with colored pollutants.

Chromatography is a classic method with relatively low degree of automation; nonetheless its ability to separate constituents of multifaceted mixtures, like those present in certain pharmaceuticals or pesticides, is very remarkable. HPLC is capable of separating the products of degradation and at the same time, the detection of such intermediates or byproducts is made possible. Detection is done using either UV or mass spectrometry, depending on what compound is being detected. With this method, researchers are able to find out whether complete mineralization of the pollutant in question has taken place, or whether it has merely transformed into another hazardous compound.

TOC analysis uses the Total Organic Carbon method to assess the degree of mineralization. As opposed to UV-Vis spectrophotometry and HPLC, which focus on identifying certain compounds, TOC measures the carbon concentration in the solution (Gopinath et al., 2022). TOC plays a vital role in confirming the safety of the process for the environment since any significant drop in TOC value is a sign of the conversion of organic matter to inorganic compounds such as CO^2 and H^2O which indicates complete degradation.

These analytical techniques combined provide a comprehensive overview of the functioning of the catalysts, reaction rates and their environmental effects.

Control experiments offer proof of the efficacy of newly developed green catalysts and demonstrate that the degradation observed is truly due to the catalyst. The most popular control setups include blank reactions which are performed with no catalyst or light, as well as with set temperature and pH, and then measure the extent to which degradation occurs through photolysis or natural attenuation.

Degradation, as a byproduct of thermal or chemical processes in the absence of light, is not a concern under dark controls for photocatalytic studies. This corresponds to catalyst-only controls in which the catalyst is illuminated and placed in solution but the pollutant is not present. It allows us to confirm that there is no degradation from catalyst instability or leaching of some poisonous compounds (Boulkhessaim et al., 2022). The commercial catalyst comparison is the stage at which green catalysts get assessed against standard catalysts which include commercially available TiO_2 or Fenton reagents. They are then verified alongside the competition in terms of performance, cost, and environmental impact.

All these controls improve precision in isolating factors involved in pollutant remediation and in achieving the desired outcome. They also support the corroborating hypothesis that green catalysts do not only serve their intended purposes, but are indeed safer and more environmentally friendly than traditional systems.

Accomplishing the cost-effective degradation of organic pollutants utilizing sustainable catalysts requires an integrated framework involving selection of the catalyst, optimization of degradation conditions, and validation against analytical benchmarks. The methodological framework outlined above will ensure the validity of the results while enabling the development of integrated, effective, and cleaner solution technologies for pollution remediation. This holistic approach further embodies the principles of green chemistry and adds to the emerging environmental remediation technologies aimed at addressing water quality challenges down the line.

RESULTS

Types of Organic Pollutants Overview and Their Effects on the Environment

Organic pollutants are usually made of carbon-based chemical structures that tend to persist in nature. These include synthetic dyes, pharmaceuticals, pesticides, petrochemicals, phenolic compounds, and plasticizers such as phthalates and bisphenol A. Each category is derived from different sources and poses a unique threat to the environment. For example, synthetic dyes used in textile and printing industries are non-biodegradable and toxic to aquatic ecosystems due to their vibrant colors and complex structures. Pharmaceuticals, including antibiotics, hormones, and anti-inflammatory medicine, are commonly disposed of, excreted, and released into waterways along with wastewater from hospitals and drug manufacturing plants (Boulkhessaim et al., 2022). Their presence, even in traces, is known to promote antimicrobial resistance and disrupt endocrine system functions of aquatic life. Pesticides, most importantly the persistent organic pollutants like DDT and organophosphate pesticides, are widely utilized in agriculture and tend to bioaccumulate, which makes them toxic to non-target organisms, including birds and humans. These pollutants are not removable with conventional techniques of wastewater treatment, and therefore, contaminate water and soil, which in turn causes imbalance in the ecosystem, health problems, and degradation of the environment for an extended period of time. The stubborn behavior and harmful aspects of these substances highlight the necessity for new treatment methods that are both efficient and safe for the environment.

Development of Catalytic Degradation (Homogeneous and Heterogeneous Catalysis)

The importance of catalysis in the breakdown of pollutants started with the attempts to purify water through catalytic oxidation processes during the early 1900s. Since that period, two types of catalytic systems have emerged: homogeneous and heterogeneous catalysis. Homogeneous catalysts, which exist in the same phase as the reactants, are often some form of a soluble metal complex or an acid. These catalysts usually have fast reaction rates and high selectivity, but the effluent poses difficulties with removal because it is intertwined with secondary pollution risks. In contrast, heterogeneous catalysts exist in a different phase, which are usually solid catalysts in a liquid or gaseous reaction mixture (Bala et al., 2022). Heterogeneous catalysis is more widespread because of ease of separation and reusability, as well as being more favorable for continuous processes. Some early examples include the use of transition metal oxides like TiO2 and MnO2 in oxidative degradation processes. Eventually, catalytic systems became more sophisticated with designs such as Fenton and photo-Fenton reactions where iron catalysts produce hydroxyl radicals to oxidize pollutants. Since then, catalysis has been at the core of advanced oxidation processes (AOPs), but the invariable catalysts used are toxic and rely on significant quantities of metals, high energy input, or hazardous reagents that greatly affect the environment.

As a result, the reliance on non-renewable and possibly hazardous catalytic materials in the past has shifted the focus of research towards more sustainable and environmentally friendly alternatives in the last few decades.

Principles of Green Chemistry relative to Degradation of Pollutants

The ideas of 'Green Chemistry' began with Paul Anastas and John Warner in the 1990s. These ideas seek to re-engineer the design of processes and materials in chemistry such that the steps taken contain the use of, or completely eliminate the generation of, hazardous substances. In the context of pollutant degradation, green chemistry focuses on sustainability, energy conservation, and safety. As it pertains to the twelve principles of green chemistry including sustainable feedstocks and safer solvents like Design for Degradation and Catalysis frameworks, efforts are geared towards developing advanced technologies for the treatment of green pollutants (Kumar, 2021). Regarding the case of organic pollutant degradation, these principles suggest an approach one should take from high temperature processes employing hazardous oxidants, unrecoverable catalysts to mild condition methods employing nature's and biodegradable materials with non-toxic by-products. To illustrate, the approach would involve the replacement of chlorine oxidants with solar activated photocatalysts or using reducing agents extracted from plants instead of synthetic chemicals. Also, the principle of catalysis which encourages employing catalysts instead of stoichiometric reagents to achieve a desired goal at a minimal input allows reactions to be driven with little material added. Adoption of the principles from green chemistry increases the safety and the processes involved in the degradation of pollutants while at the same time aligning scholarly work with international targets like the United Nations Sustainable Development Goals (SDGs).

Kinds of Green Catalysts (Plant-Extract Based, Metal-Free, Biochar Supported, Enzyme Based)

The development of green catalysts is a significant advance in green technology as they focus on eco-friendly materials and methods to address environmental challenges. Various types of green catalysts that utilize plant or environmentally friendly materials have been developed. Plant extract based catalysts use phytochemicals as reducers and stabilizers for the production of metal or metal oxide nanoparticles. Nanoparticles generated from green methods (for instance, using neem, citrus peels and tea) have high surface activity and can chemically degrade dyes and pharmaceutical products through redox reactions or photocatalytic processes. Non-metallic catalysts like graphitic carbon nitride (g-C_3N_4) and doped graphene are gaining popularity as they do not use poisonous metals to oxidatively catalyze reactions (Bhatt et al., 2022). These materials, activated by sunlight or mild oxidants, are also able to efficiently convert organic molecules into harmless byproducts. Biochar supported catalysts have recently emerged, which include biochar (a carbon-rich product of biomass pyrolysis) functionalized with catalytic agents like Fe or Mn oxides. Biochar, due to its high surface area and porous structure, can adsorb a large amount of pollutants and degrade them.

Last but not the least, laccase, peroxidase, and tyrosinase are examples of enzyme catalysts that provide optimized and specific degradation pathways of phenols, dyes, and drugs even at room temperature. These biocatalysts are non rudimentary, as they are readily biodegradable and non-toxic toward living organisms, and work in water, making them effective for green wastewater treatment. The various kinds of green catalysts enable researchers to customize approaches according to the type of pollutants, desired treatment conditions, and ecological consequences.

Key Previous Studies and Gaps in Literature

In the last two decades, numerous studies have shown the promise that green catalysts have in deteriorating persistent organic pollutants. For instance, some studies have shown that plant-derived compounds enhance the photocatalytic degradation of azo dyes using sunlight, lowering energy dependence through the use of TiO_2 nanoparticles. Research by Sharma et al. (2020) demonstrated the effectiveness of methyl orange dye removal using lemon peel extract iron oxide nanoparticles under visible light within 30 minutes. An equally effective technique is enzyme based degradation, laccase for instance; immobilized laccase showed Mohapatra et al. (2018) over 90% removal of diclofenac. Also, biochar supported MnO_2 catalysts have been reported to possess great removal efficiencies of antibiotics and heavy metals in wastewater matrices (Singh et al., 2021). Notwithstanding these impressive findings, gaps in research do exist, and quite a few, in fact. Most of the work was done on a laboratory scale model, with nearly no work done on pilot-scale or real wastewaters, which brings into question the affordability and practicality of these solutions. The other gap is lack of mechanistic examination concerning the by-products' toxicity as well as the degradation pathways. More often than not, the compounds formed through incomplete degradation are typically more harmful than the original pollutants.

Third, maintaining long-term stability, reusability, and sturdy enzyme-based green catalysts is still complex due to temperature, pH, and fouling sensitivity. Lack of standardized evaluation procedures makes inter-study comparison of green catalysts' efficiency difficult, and addressing this gap through interdisciplinary collaboration is crucial for advancing green catalysis from lab-scale innovations to real environmental solutions.

The nature of organic pollutants and the inadequacy of conventional treatment methods highlights the need for alternative approaches. The history of catalysis, driven by the principles of green chemistry, creates an ecosystem of diverse green catalysts, including plant-based, metal-free, biochar-supported, and enzyme-driven systems (Haruna et al., 2024). Recent studies spotlight these catalysts' possibilities, yet issues of scalability, mechanistic understanding, and sustained performance still exist. Conducting targeted research will enable bridging these gaps toward the extensive use of green catalysts for environmental remediation while facilitating the global shift toward cleaner and safer sustainable technologies.

CONCLUSION

As earlier mentioned, the use of green catalysts for degrading organic pollutants is a new development in water purification and environmental restoration. Research on biochar-supported systems, biosynthesized nanoparticles, and enzyme based catalysts show relatively high rates of degradation compared to the ecological cost and reasonable damage to the catalyst's lifespan. The catalysts perform radical oxidation and adsorption of pollutants, and with the help of goal conservation global sustainability targets, green technology is achieved. There is significantly reduced ecological footprint associated with the wastewater treatment which enables the paradigm shift from material and resource consumption to waste created to value creation and circular economy contribution. This research in environmental science demonstrates that green catalysts may surpass traditional methods in terms of safety and friendliness to the ecosystem. Holistic approaches present further stages of the research that tackle the system's stability, scalability, and ecosystem-specific tailoring. AI and digital modeling aimed at improving catalyst lifespan, system multifunctionality, and eliminating system merger silos are the focus of multi-functional future studies. Investigating novel biocatalysts from the ocean and extremophiles has the potential to develop groundbreaking degradation systems. With further progress in this area, green catalysts will be at the forefront of transforming technologies for global sustainable water treatment and pollution management.

References

1. Ahmad, I., Aftab, M.A., Fatima, A., Mekkey, S.D., Melhi, S. and Ikram, S., 2024. A comprehensive review on the advancement of transition metals incorporated on functional magnetic nanocomposites for the catalytic reduction and photocatalytic degradation of organic pollutants. Coordination Chemistry Reviews, 514, p.215904.

2. Haruna, A., Zango, Z.U., Tanimu, G., Izuagie, T., Musa, S.G., Garba, Z.N. and Merican, Z.M.A., 2024. A critical review on recent trends in metal-organic framework-based composites as sustainable catalysts for environmental applications. Journal of Environmental Chemical Engineering, p.113542.

3. Deng, F., Shi, H., Guo, Y., Luo, X. and Zhou, J., 2021. Engineering paths of sustainable and green photocatalytic degradation technology for pharmaceuticals and organic contaminants of emerging concern. Current Opinion in Green and Sustainable Chemistry, 29, p.100465.

4. Boulkhessaim, S., Gacem, A., Khan, S.H., Amari, A., Yadav, V.K., Harharah, H.N., Elkhaleefa, A.M., Yadav, K.K., Rather, S.U., Ahn, H.J. and Jeon, B.H., 2022. Emerging trends in the remediation of persistent organic pollutants using nanomaterials and related processes: A review. Nanomaterials, 12(13), p.2148.

5. Taoufik, N., Sadiq, M.H., Abdennouri, M., Qourzal, S., Khataee, A., Sillanpää, M. and Barka, N., 2022. Recent advances in the synthesis and environmental catalytic applications of layered double hydroxides-based materials for degradation of emerging pollutants through advanced oxidation processes. Materials Research Bulletin, 154, p.111924.

6. De Farias, M.B., Prediger, P. and Vieira, M.G.A., 2022. Conventional and green-synthesized

nanomaterials applied for the adsorption and/or degradation of phenol: A recent overview. Journal of Cleaner Production, 367, p.132980.

7. Bala, S., Garg, D., Thirumalesh, B.V., Sharma, M., Sridhar, K., Inbaraj, B.S. and Tripathi, M., 2022. Recent strategies for bioremediation of emerging pollutants: a review for a green and sustainable environment. Toxics, 10(8), p.484.
8. Kumar, B., 2021. Green synthesis of gold, silver, and iron nanoparticles for the degradation of organic pollutants in wastewater. Journal of Composites Science, 5(8), p.219.
9. Wang, L., Luo, D., Hamdaoui, O., Vasseghian, Y., Momotko, M., Boczkaj, G., Kyzas, G.Z. and Wang, C., 2023. Bibliometric analysis and literature review of ultrasound-assisted degradation of organic pollutants. Science of the Total Environment, 876, p.162551.
10. Nasrollahzadeh, M., Sajjadi, M., Iravani, S. and Varma, R.S., 2021. Green-synthesized nanocatalysts and nanomaterials for water treatment: Current challenges and future perspectives. Journal of hazardous materials, 401, p.123401.
11. Krishnan, A., Swarnalal, A., Das, D., Krishnan, M., Saji, V.S. and Shibli, S.M.A., 2024. A review on transition metal oxides based photocatalysts for degradation of synthetic organic pollutants. Journal of Environmental Sciences, 139, pp.389-417.
12. Ahsan, W.A., Hussain, A., Lin, C. and Nguyen, M.K., 2023. Biodegradation of different types of bioplastics through composting—a recent trend in green recycling. Catalysts, 13(2), p.294.
13. Bhatt, P., Pandey, S.C., Joshi, S., Chaudhary, P., Pathak, V.M., Huang, Y., Wu, X., Zhou, Z. and Chen, S., 2022. Nanobioremediation: A sustainable approach for the removal of toxic pollutants from the environment. Journal of Hazardous Materials, 427, p.128033.
14. Ganjali, F., Kashtiaray, A., Zarei-Shokat, S., Taheri-Ledari, R. and Maleki, A., 2022. Functionalized hybrid magnetic catalytic systems on micro-and nanoscale utilized in organic synthesis and degradation of dyes. Nanoscale Advances, 4(5), pp.1263-1307.
15. Singh, A.K., Bilal, M., Iqbal, H.M. and Raj, A., 2021. Trends in predictive biodegradation for sustainable mitigation of environmental pollutants: Recent progress and future outlook. Science of The Total Environment, 770, p.144561.
16. Gopinath, A., Pisharody, L., Popat, A. and Nidheesh, P.V., 2022. Supported catalysts for heterogeneous electro-Fenton processes: Recent trends and future directions. Current Opinion in Solid State and Materials Science, 26(2), p.100981.