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Green Catalysis for Waste Minimization: Strategies for Resource-Efficient and Sustainable Industrial Chemical Processes

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Abstract

The production of industrial chemicals is essential to modern society and requires significant amounts of raw materials, solvents, energy, and water, and produces solid, liquid, and gaseous wastes. One of the significant steps to mitigate them is green catalysis, which involves improving the selectivity of the reactions, atom efficiency, energy efficiency, catalyst recovery, and use of waste feedstocks in the production of valuable products. In this context, the reduction of waste generated and the processing of the chemicals in an environmentally friendly way are discussed critically with regard to the use of green catalytic technologies. A systematic literature-based research design was followed. Relevant literature on green catalysis and waste minimization, waste valorization, catalyst recycling, and sustainable catalysis, which, was deemed relevant for the topic of this review, was sourced using a combination of terms from a variety of major scholarly databases. Peer-reviewed publications were identified by searching the major scholarly databases with combinations of the following terms: green catalysis, waste minimization, resource efficiency, sustainable catalysis, waste valorization, catalyst recycling, and circular economy. Only those studies that were relevant to the issues of conversion, selectivity, recyclability, resource utilization, and environmental performance were considered and only those studies that were found to have the appropriate methodological standard were evaluated. The evidence reviewed confirms that heterogeneous catalysis, biocatalysis, photocatalysis, electrocatalysis, single-atom catalysis, and catalytic waste valorization can contribute to reducing the amount of waste due to their ability to achieve more selective transformations, less stoichiometric (excess) amounts of reagents, less harsh reaction conditions, re-use of the catalysts, and use of renewable or waste material as starting materials. But there are some limitations, like catalyst deactivation, critical material requirements, solvent effects, separation requirements, scale-up, economy, and life cycle assessment. This green catalysis should be combined with the ideas of process

intensification, renewable energy, design for circular economy and quantification of sustainability to make industrial chemistry truly resource efficient.

Keywords: Green catalysis, Waste minimization, Resource efficiency, Sustainable chemistry, Waste valorization, Circular economy.

I. INTRODUCTION

The chemical industry plays an essential role in today's economic development, providing pharmaceuticals, polymers, fertilizers, fuels, agrochemicals, solvents, coatings and advanced materials. Conventional chemical production, on the other hand, involves high raw material, fossil fuel, solvent, water, and energy use, product by-products, and process waste. In the past, the product yield was often used as an indicator of process efficiency, but high product yield does not necessarily lead to low resource use or low environmental impacts. Hence, the objective of green chemistry is to avoid the formation of waste and hazardous substances in the very initial stage of the chemical process. The overall objective of green chemistry is to avoid the generation of waste and hazardous materials at the "upstream" part of the chemical process (Anastas & Warner, 1998; Sheldon, 2012). In this regard, green catalysis is emerged as an important approach to enhance the material and environmental efficiency of industrial chemical processes. The concept of catalysis is closely linked to a number of fundamental principles of green chemistry, such as the avoidance of waste, the principle of atom economy, the efficiency of energy use and safer chemical synthesis. Catalysts can aid a chemical change, but do not react in any measurable amount and can make the change more selective. This means that catalytic processes need less of the reagents, decrease unwanted side reactions, and decrease waste production. Sheldon (2012) introduced the notion of correlation between atom economy, step economy and E-factor as useful tools to assess the efficiency of chemical reactions and the role of homogeneous, heterogeneous, organocatalytic and biocatalytic systems in waste minimization. Catalysis is thus an important element of the goals to redefine chemical synthesis around efficiency and prevention of pollution.

This has been reaffirmed by the E-factor that defines waste as being anything that's produced that's not the product. However, this idea is shifting from an efficiency (or chemical yield) model towards a more waste reduction based model (Sheldon, 2023). Pollution prevention and sustainable chemical production in this context can be achieved through catalysis, non-fossil reaction media, renewable feedstocks, circular economy and renewable-energy based electrification. The use of a "greener" catalyst instead of a traditional catalyst is not the only aspect of green catalysis. Sustainability of a catalytic process depends on the preparation of catalysts, source of feedstock, amount of catalyst required, activity, selectivity, lifetime, regeneration and recyclability of catalysts, requirement for solvent, recovery/energy, end-of-life management and toxicity. A high activity catalyst which requires a small amount of rare and toxic materials or a large amount of solvent, or consumes large amounts of energy to regenerate, may not be sufficiently environmentally advantageous overall. The trend of incorporating increasing number of resource-efficient and life cycle viewpoints together with catalytic performance is increasing (Yenare et al., 2025).

The connection of green catalysis to the circular economy is also becoming a topical issue. Chemical circularity is all about minimizing the need for primary materials, adding value to the material, maximizing the re-use of the waste stream, and minimizing the material loops in chemical production. Catalytic technologies can help to achieve these objectives by converting biomass, plastics, carbon dioxide, and other waste streams to fuels, monomers, platform chemicals, and functional materials. Wattanakit et al.(2024) acknowledge that three

approaches—green chemistry, catalysis and waste valorization, are highly interdependent and are potential strategies for increasing resource efficiency and circularity. These developments have taken place, but there are still critical issues to address. The most common catalytic study deals with conversions and yields, and is lacking in detail regarding the preparation of the catalyst, recovery of the solvent, energy use, production of wastes, and life-cycle impacts. Furthermore, scale-up of the process is limited for some cases due to substrate scope, separation issues, catalyst deactivation, and limited substrate scope, as well as economic issues (Yenare et al., 2025). Therefore, a systematical assessment of green catalysis is needed to comprehend that how catalytic technologies can achieve all these three goals: decrease waste, conserve the resources and in technical and economic terms be viable. The aim of this review is thus the recent advances in green catalysis with a special emphasis on waste prevention, recovery of the catalysts, alternative reaction media, waste valorization, resource efficiency and transition towards sustainable and circular industrial chemical processes.

II. OBJECTIVE OF THE STUDY

The goal of this review is to critically assess how the green catalytic technologies contribute to the reduction of industrial waste and improvement of the chemical industry's efficiency, sustainability and circularity.

III. LITERATURE REVIEW

This review's theoretical underpinning is based on the concepts of green chemistry, pollution prevention, E-factor and resource efficiency, as well as theory of circular economy. The key elements of green chemistry are to avoid the use of waste and hazardous materials, and to design chemical products and processes that are waste-free and hazard-free. A particular role in this context is played by catalysis, which can make the reaction more efficient, more selective and more efficient in terms of atom economy and usage and decrease the quantity of stoichiometric reagents. Sheldon (2012) introduced the concepts of atom economy, step economy, and E-factor as an effective tool for evaluating the efficiency of reactions, and demonstrated the ability of homogeneous, heterogeneous, organocatalytic and biocatalytic methods to reduce waste. In the theoretical sense, the idea of Catalytic Process Design is a direct connection between the pollution prevention and chemical efficiency. E factor could be a helpful measure for waste reduction. It is defined as the amount of waste produced per amount of waste generated of the desired product generated and need not be the usual yield from the reaction. Sheldon (2017) highlighted the importance of using atom economy, E-factor and process mass intensity (PMI) as mass-based indicators of the efficiency of the chemical process and recommended that these be used alongside the measurement of LCA and economics. More recently Sheldon (2023) reconfirmed the E-factor and its use to shift the focus of efficiency from high production yields to preventing waste at source, highlighting the link between catalysis and other alternatives to the use of solvents, renewable resource, circularity and electrification.

It is also known from literature that a catalyst can have its design coupled with that of the process. Supported catalysts, advanced heterogeneous catalysts and catalysts with single atom can achieve not only high catalytic activity and selectivity, but also to separate and even increase the use efficiency of the catalysts. Wang et al. (2024) presented the definition of high atomic utilization catalysts with well-defined active sites as single-atom catalysts, and Shang et al. (2024) pointed out that these are now widely used in CO₂ conversion. But the sustainability of these catalysts relies on different factors like catalyst synthesis, stability, regeneration, metal availability and scalability, etc. Another significant challenge for atomic catalysts mentioned by Tang et al. (2024) is the controlled synthesis. Bio-catalysis, where enzymes are able to offer a

high level of chemo-, regio- and stereo-selectivity at relatively mild conditions, is another route of great relevance with respect to the use of resources for the production of chemicals. Sheldon (2012) also reported that biocatalysis is one of the ways to decrease the waste; more recently, immobilized enzymes and continuous flow systems were developed. Immobilized biocatalysts in monolithic flow reactors can provide space-time productivity, decrease reaction volume and solvent. In addition, Söderberg et al. (2024) demonstrate that, besides the performance of the reaction, the toxicity and environmental properties of the substrates and products involved in a sustainable biocatalysis reaction need to be considered.

Another aspect of the idea of green catalytic design is the design of alternative reaction media. Due to their tunable physicochemical properties, low vapor pressures, and function as solvents, catalysts, and/or functionalization media, DESs have been of interest (Ma et al., 2024; Yu et al., 2024). According to Wang et al. (2024), hydrophobic DESs are capable of undergoing biocatalytic transformations with yields of up to 95.1% and a reaction time of 2 h, in a model esterification system. However, the “green” designation of a solvent is not only based on its volatility and biodegradability, but also involves preparing the solvent, its toxicity, its persistence and its life-cycle effects and recovery. Recently, photocatalysis and electrocatalysis are added to green catalysis. Photocatalytic plastic upcycling is a promising emerging strategy to convert plastic wastes into valuable chemicals under relatively mild conditions according to Ran et al. (2024). Conventional chemical reducing or oxidizing agents can be replaced by electricity in electrocatalysis, which can help to minimize reagent waste. Wang et al. (2024) review the electrocatalytic upgrading of molecules derived from biomass and Tang et al. (2024) review the structural engineering of the atomic catalysts for electrocatalytic reactions. But selectivity, energy efficiency, stability of the electrode/catalyst and processes scale up to the industrial level remain a challenge to be tackled for these technologies.

This is particularly the case in the field of waste valorization and in green catalysis and the connection between these two is very important. Wattanakit et al. propose green chemistry and catalysis, and waste valorization, to enhance the efficiency of resources and to create material loops. Catalytic depolymerization of polyester waste has the potential for closed-loop recycling and upcycling, through the creation of valuable chemical feedstocks (Weng et al., 2024). Ionic liquids and DESs can also be used for catalyzing the conversion of lignin to valuable chemicals (Singh et al., 2024) and shell wastes can also be catalytically converted to useful chemicals (Korampattu et al., 2024). All of the above approaches result in a waste-to-waste mentality and not waste to environment. Although some advances have been made, there are some research gaps to be filled. Several catalytic studies are still conducted that report on conversion, yield and selectivity but do not report in a systematic way the E-factor, PMI, energy demand, catalyst life-time, solvent recovery or life-cycle impacts. Secondly, sustainability assessments do not always include the synthesis and regeneration of catalysts, or end-of-life. Thirdly, laboratory tests do not cover the industrial mass balance, economic aspects and the long term results of a catalyst. Fourth, making direct comparisons amongst the catalytic technologies is difficult due to differences in feedstocks, conditions, metrics and system boundaries employed in these studies. Moreover, Yenare et al (2025) point out that catalyst deactivation, substrate limitations, catalyst reusability and economic scale up continue to be challenges to industrialization.

Hence, the identified research gap for this review is the lack of integrated assessment of green catalysis, which involves the preservation of waste, utilization of limited resources, sustainability of the catalyst, valorization of waste and its application to the industry. Sustainability is not only related to catalytic yield, but rather it is a wider perspective that

includes the catalytic activity and material efficiency, waste minimization, circularity and process sustainability.

IV. RESEARCH METHOD

In the present work, the systematic critical reviewing design was used to integrate and critically review literature available on green catalysis and waste minimization in industrial chemical processes. There were no laboratories and human subjects involved in this study, so the major unit of analysis was the published scientific study. The relevant literature was retrieved by a systematic search of the major scientific databases (Web of Science, Scopus, ScienceDirect, SpringerLink, PubMed, ACS Publications, Wiley Online Library and the Royal Society of Chemistry). A combination of keywords and Boolean operators was used to cover the main themes including those of green catalysis, sustainable catalysis, minimization or recycling of waste, resource efficiency, circular economy, catalyst recycling, valorization of waste, biocatalysis, photocatalysis, electrocatalysis, upcycling of plastics, conversion of biomass, utilization of CO₂, green solvents and industrial chemical processes. The papers from the past are selected with particular focus on the papers published since 2020 that were considered as peer reviewed and other seminal older papers have been included as needed to provide baseline concepts such as atom economy, E factor, catalysis and green chemistry. Only studies that addressed clearly relevant catalytic transformations or process design with relevance to the environmental aspects of waste prevention, resource efficiency, sustainability/waste valorization and contained enough data to assess the catalytic/process performance were included. Studies excluded were ones that were directly related to conventional catalysis but did not involve any aspect of sustainability. The data have been systematically collected based on the type of catalyst, feedstock, the type of reaction, operating conditions, conversion, yield, selectivity, catalyst recovery and lifespan, solvent/Reaction medium, energy source, mechanism of reduction of waste and sustainability indicators. Also, atom economy, E-factor, process mass intensity, carbon efficiency, energy demand and life-cycle assessment were also identified, where applicable. Themes of catalytic efficiency, recyclability, alternative reaction media, process intensification, renewable feedstocks, waste valorization and circularity were identified and analyzed using thematic and comparative analysis. There were some significant differences in materials, conditions, scale and evaluations used, and so the quantitative results of the studies reviewed were not statistically combined. Instead, the findings from each of the individual studies were compared and contrasted and analyzed to identify emerging technologies, key sustainability mechanisms and the scope for less industrial chemical waste.

V. FINDINGS & DISCUSSION

Overview of the Evidence: The literature shows that green catalysis can play a role in waste minimization by various interrelated pathways, not a single technology. The most common mechanisms that have been found are selectivity enhancement, increased atom efficiency, using stoichiometric reagents, lessening the severity of the reaction, catalyst recovery and reuse, solvent reduction or substitution, waste feedstocks to useful products, and integration with renewable energy.

Table 1. Major green catalytic strategies for waste minimization

Catalytic strategy	Principal waste-minimization mechanism	Major resource benefit	Important limitation
Heterogeneous catalysis	Low activity/selectivity	Efficient molecular transformations	Separation of catalyst
Biocatalysis	High chemo-/regio-/stereoselectivity	Mild conditions and fewer by-products	Enzyme stability and substrate limitations
Photocatalysis	Light-driven activation	Potentially lower thermal energy demand	Light efficiency and scale-up
Electrocatalysis	Electrons instead of some chemical reagents	Potential coupling with renewable electricity	Electrode stability and energy efficiency
Organocatalysis	Metal-free transformations	Avoids some critical metals	Catalyst loading and separation
Single-atom catalysis	High atomic utilization	Efficient use of active metals	Stability and manufacturing complexity
Waste-derived catalysis	Waste as catalyst/feedstock	Supports circularity	Variability of feedstock
Catalytic plastic recycling	Polymer waste converted into chemicals	Reduces virgin feedstock demand	Product separation and economics
Biomass catalysis	Use of renewable residues as chemicals	Substitution of fossil resources	Heterogeneity of the feedstock

A better Selectivity and Atom Economy: A key role of catalysis in minimizing waste is its potential to make more precise direction of chemical reactions. High selectivity decreases undesirable side reactions, by-products, purification needs, use of solvents, and losses of materials. Catalysis can also help to enhance atom economy in terms of the percentage of reactants that are used to make the product. The ability of molecular precision to minimize synthetic steps, resource usage, and waste is exemplified by recent developments in regioselective and stereoselective catalysis. Yenare et al. (2025) highlight the importance of precision catalytic transformations in the pharmaceutical and fine-chemical industries, where complex multistep synthesis can lead to significant waste generation. Catalytic hydrogenation, carbonylation, hydroformylation and metathesis have thus helped to develop more efficient alternatives to traditional stoichiometric processes.

Heterogeneous Catalysis and Catalyst Reuse: Because solid catalysts can be separated by filtration, sedimentation, centrifugation, and/or magnetic separation, there are many opportunities to reduce waste in the use of heterogeneous catalysts. This is achieved through effective recovery and reuse, thereby reducing the amount of catalyst used and improving catalyst life. More advanced materials, such as supported nanoparticles, hierarchical structures, porous catalysts, and single atom catalysts (SACs) are being studied and explored because they can offer highly utilized and well defined catalytic sites. SACs are promising for hydrogen production, hydrogenation and CO₂ conversion. But recyclability of the catalyst is not enough to ensure sustainability. In addition to this, the overall environmental performance of the catalyst

should be taken into account when preparing it, when it needs to be regenerated, when the catalyst is leached with metals, when energy is used to prepare it and when it is disposed of.

Biocatalysis: Another important pathway is also biocatalysis, as enzymes can catalyse highly selective reactions under relatively mild temperature and pressure conditions. They are highly chemo-, regio- and stereoselective, which may minimize side reactions and purification steps. Recent studies have fused the concepts of biocatalysis, enzyme immobilisation, continuous processing and cascade reactions. Lambarska et al. (2024) point out the promising opportunities of monolithic porous supports for increasing the stability, immobilization, continuous operation, and cofactor regeneration of enzymes. In addition, Söderberg et al. (2024) underline sustainability-by-design, and point out that the assessment should take into account the toxicity and environmental properties of catalysts as well as their substrates and products.

Alternative Reaction Media: The 'material and environmental impact' from chemical manufacturing can be a significant portion of the solvents used. Therefore, reactions done without solvents, reactions done in water, recyclable solvents, ionic liquids, and deep eutectic solvents (DESs) have been gaining in interest. The environmental advantages of DESs are dependent upon their composition, toxicity, biodegradability, preparation, and recovery, and they have tunable properties in addition to low vapor pressure. Wang et al. (2024) found that the yields of enzymatic reactions were up to 95.1% in the cases of the hydrophobic DESs and that the activity of the enzymes was affected by the polarity and viscosity of the DESs. Therefore, the overall process and life cycle impacts of reaction media must be assessed and not just take on the tag of being "green."

Photocatalysis and Electrocatalysis: Photocatalysis may be the process to induce chemical changes when exposed to light, thus lowering the need for conventional thermal energy. It has been of special interest in plastic upcycling, where it has been possible to convert persistent polymers into valuable chemicals, relatively mild conditions (Ran et al., 2024; Mountanea et al., 2024). Other photocatalytic materials like TiO_2 , ZnO and SnO_2 have been explored for wastewater treatment. However, the production of the catalyst, the energy of the light-source, recovery, and scale-up should be considered in addition to the efficiency of removal. The electron is directly employed as a redox reagent in electrocatalysis, which can reduce the reliance on chemical oxidants and reductants. Wang et al. (2024) conducted a review on the electroreductive upgrading of biomass derived compounds such as levulinic acid, hydroxymethylfurfural, furfural, phenol and guaiacol. It has great potential for sustainability, if there is selectivity, if it is electricity efficient, if the electrodes are durable, and if the electricity source is renewable.

Catalytic Plastic Waste Valorization.: Plastic waste can be transformed into monomers, oligomers, fuels and chemical intermediates using catalytic depolymerization and upcycling. Weng et al. (2024) state that catalytic chemical recycling is a potentially viable solution for the recovery of the carbon content in polyester waste and for lowering the reliance on virgin feedstocks. Other catalytic pathways for converting polymers to value added products are also available, which are referred to as photocatalytic routes. The catalytic approaches, taken together, are intended to enable transition from the traditional waste disposal paradigm to the paradigm of resource recovery, waste prevention, and circular chemical production.

Table 2. Catalytic pathways for waste valorization

Waste/resource	Catalytic pathway	Potential product
Aromatic plastics	Hydrolysis, alcoholysis, hydrogenolysis	Aromatics, oligomers, fuels
Emissions from burning plastics	Photocatalytic/thermocatalytic oxidation	Oxygenated chemicals
Lignin	Pyrolysis	Aromatic chemicals
Agri-residue, catalytic conversion of residues	Platform chemicals and fuels	Agri-residue, catalytic conversion of residues
Shell waste	Catalytic/thermochemical conversion	Chemicals and functional materials
CO ₂	Hydrogenation/electroreduction	Methane, alcohols, carbon-based products
Waste oils	Catalytic transesterification/hydrogenation	Biodiesel and renewable hydrocarbons
Spent catalysts	Recovery/reprocessing	Reusable catalytic materials

Agricultural waste and biomass: Fossil-based feedstocks can be replaced by biomass and agricultural residues, especially if non-food wastes are being valued. Catalytic conversion of biomass can generate useful platform chemicals, fuels, solvents and materials and foster circular use of resources. Singh et al. (2024) conducted a review on catalytic lignin conversion using ionic liquids and deep eutectic solvents that highlighted the potential use of other reaction media to enhance the solubilization of lignin and conversion to value-added chemicals. Likewise Korampattu et al. (2024) pointed out that shell wastes are also an underutilized chemical resource that can complement the conventional lignocellulosic biorefineries. Importantly, biomass can also be used as a precursor to catalysts, which can lead to a biomass to catalyst to product cycle that can lessen reliance on fossil-derived materials.

CO₂ Conversion: Another significant route for CO₂ to be utilized is through the use of a waste stream as a resource. CO₂ can be used as building blocks for catalytic conversion to fuels, alcohols, carbon-based materials, and other chemical intermediates. Single-atom catalysts (SACs) have garnered significant interest due to the precise control of their active sites, which can impact CO₂ activation and product selectivity. Shang et al. (2024) stated that the central metal atom, coordination environment, support effects and interactions of active sites play an important role. Choudhary et al. (2024) also pointed out the importance of hydrogen dissociation and intermediate binding in CO₂ methanation with a SAC. But CO₂ utilization does not automatically translate to carbon negativity because the climate impact of CO₂ utilization depends on the energy source, the hydrogen source, the catalyst lifetime, the durability of the product and the overall carbon balance.

Waste-Derived Catalysts: A novel approach is the "catalystization of wastes" whereby two waste streams are solved by converting waste materials to catalysts. Carbon catalysts derived from biomass are of special interest due to their renewable nature and low cost. Wastes can also serve as appropriate carbon frameworks that can be used to support the individual metal atoms. Wattanakit et al. (2024) reported hydrocracking catalyst residues to be transformed into NiS/porous carbon materials and PET waste to be transformed into activated carbon. These are examples of moving away from the traditional waste management concept of disposal to the concept of producing a resource from waste.

The impact of the PIS approach on sustainability metrics: Catalytic efficiency can be optimized by process intensification, such as continuous flow processing, which involves better heat and mass transfer, smaller reactor size and better process control. When used in conjunction with immobilized biocatalysts, this can help to retain the catalyst in place and keep the process running. But, catalyst performance should be judged in terms of separation, solvent and energy requirements. So there is no single indicator that reflects sustainability. To evaluate the overall environmental performance of catalytic processes, one should consider atom economy, E-factor, process mass intensity, carbon efficiency, energy demand, catalyst lifetime, waste generation and life-cycle impacts.

Table 3. Important sustainability metrics

Metric	Primary purpose	Interpretation
Atom Economy (AE)	Measures incorporation of reactant atoms into product	High better.
E-factor	Measures waste relative to product	Lower generally preferable
Process Mass Intensity (PMI)	Measures total mass input per mass product	Lower generally preferable
Reaction Mass Efficiency (RME)	Combines yield and material utilization	Higher generally preferable
Carbon Efficiency	Measures carbon retained in desired product	Higher generally preferable
Energy Intensity	Measures energy required per product	Lower generally preferable
Catalyst productivity	Product generated per catalyst quantity	Higher generally preferable
Turnover Number/Frequency	Measures catalyst utilization	Higher generally preferable
Life-Cycle Assessment	Assesses environmental impacts across life cycle	System-wide evaluation

Sheldon has shown that the use of E-factor, atom economy, and PMI are useful, but must be complemented by the use of life cycle assessment and economic assessment. The evidence thus points to a multi-dimensional sustainability assessment of a true green catalytic process, rather than one based on the conversion or yield value.

VI. DISCUSSION

The findings indicate that green catalysis is also a huge contributing factor to industrial waste reduction, but some of the process-level parameters must be considered for the realization of green benefits. The one that is most clearly and effectively identified is the minimisation of chemical transformation waste. Catalytic systems can help to minimize byproduct formation and the subsequent purification steps, because of their increased selectivity and atom utilization. This is a part of the basic principle of green chemistry: "Prevention is better than treatment". In the literature, it is also pointed out that the choice of the catalyst is not sufficient. Other factors, such as catalyst recovery, catalyst lifetime, regeneration, and raw material origin, are also key factors for overall sustainability. The benefit of using heterogeneous and immobilized catalysts is that they can be separated and reused; single-atom catalysts have high atomic utilization. However, their synthesis could be rather complex or require critical elements/energy. Therefore, the

environmental effect of an advanced catalyst should be evaluated during the entire process and not just based on the activity of the catalyst. A more recent systematic analysis also explores the issues of catalyst deactivation, limited reusability of the catalyst, scope of the catalyst's substrate, and scalability.

Biocatalysis is an alternative way. It has a main benefit of having a high level of selectivity under comparatively mild conditions, which can help to minimize side products and energy consumption. The overall efficiency is, however, influenced by some factors including enzyme stability, enzyme immobilization, substrate range, co-factor requirement and downstream processing. Despite the fact that immobilized enzymes/flow systems are an emerging technology, some of these drawbacks can be surmounted by process engineering, as shown in recent studies. Another important factor is the second alternative reaction media. The use of deep eutectic solvents and similar systems can decrease volatiles and offer tunable chemical environments but the status of "green solvent" is not to be considered synonymous with sustainable. The preparation, toxicity, biodegradability, viscosity, end-of-life recovery and management should be considered. They have been recently reviewed and their potential and limitations are being discussed.

The most obvious connection between green catalysis and circular economy could be waste valorization. Secondary resources can be plastic, biomass, CO₂, shell waste, and spent catalyst materials. Yet, even if waste is converted into another material, there is no guarantee that the material loop is closed. The more a process retains material value, the more circular it is; also, if it consumes fewer additional virgin resources, has suitable energy sources, and does not impose environmental costs on another process, then the more circular the process is. The possibilities of photocatalysis and electrocatalysis are significant in the future since they are connected to renewable electricity. The findings of the successful upcycling of plastics via photocatalysis and conversion of biomass through electrocatalysis indicate that the use of alternative energy inputs can be applied to replace traditional methods of transformation, both thermally and/or with reagents. However, to achieve industrial sustainability, they need to make efficient use of photons, electricity, the life of the electrode and the catalyst, the reactor design, and the electricity source. A green catalysis model emerges that integrates the design of the catalysts, the engineering of the process, the selection of the solvent, the choice of the feedstock, the energy supply, the separation of the products, the recycling, and the life cycle assessment in one system. This interpretation is in line with recent circular-economy research where catalysis is seen as a link between sustainable chemical transformation and resource circulation.

VII. CONCLUSION

A key strategy for reducing waste, enhancing utilization efficiency and promoting more environmentally friendly chemical manufacturing in the industry is green catalysis. The advantages include increased selectivity, atom economy, recovery of the catalyst, reduced amount of reagents and energy, recycling of feedstock, and utilization of waste to make valuable products. However, yield and conversion are not the only catalytic sustainability metrics, the production of the catalyst, its toxicity, energy requirement, required amount of solvents, end-of-life, and regeneration are all factors. Future research directions include the use of recyclable catalysts, materials derived from waste, continuous flow and catalysis using renewable energy. Future research directions include: Recyclable catalysts, Materials made from waste, Continuous flow and Catalysis using Renewable energy. Green catalysis can complement green chemistry with the circular economy making waste prevention and resource efficiency a part of chemical production.

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