International Journal of Interdisciplinary Innovative Research & Development (IJIIRD)

ISSN: 2456-236X

Vol. 10 Issue 01 | 2025

A review on Recent Advances in Green Chemistry for Sustainable Industrial Processes

Nitin Bharambe[1], Sandeep Khachane[2]

[1,2]Department of Applied Science & Humanities, Padm. Dr. V. B. Kolte College of Engineering, Malkapur

DOI: 10.5281/zenodo.15728200

ABSTRACT

This literature review explores the evolution and application of green chemistry principles, emphasizing the field's advancements in promoting sustainable industrial practices. Since the formalization of the "12 Principles of Green Chemistry" over two decades ago, significant progress has been made in addressing environmental challenges through innovative methodologies, materials, and applications. The review highlights the integration of concepts such as circular economy (CE) into chemical processes, aimed at enhancing resource efficiency, reducing carbon emissions, and fostering sustainable practices. Key advancements in areas such as advanced synthesis methods, green catalysis, sustainable solvents, extraction techniques, and the development of renewable materials are discussed. The review also examines sector-specific applications, particularly in pharmaceuticals, energy production, and textiles, illustrating how green chemistry principles are being implemented to reduce environmental impacts. Despite these advancements, challenges in scaling laboratory successes to industrial applications and establishing comprehensive regulatory frameworks remain. Future research directions focus on interdisciplinary collaboration, innovation, and the development of efficient, scalable processes that align with sustainability goals. This review underscores the critical role of green chemistry in addressing global environmental concerns and the need for a paradigm shift in the relationship between chemistry, industry, and the environment.

Keywords: *Green Chemistry, impact on environment, synthesis, catalysis etc*

1. Introduction and Evolution of Green Chemistry Principles

The imperative to conserve natural resources and protect the environment has led to the emergence and rapid growth of green chemistry. Since the definition of the "12 Principles of Green Chemistry" more than 20 years ago, the field has evolved significantly to address sustainability challenges in industrial processes. Green chemistry principles were formalized over two decades ago, with chemists becoming increasingly mindful of the need to conserve resources and protect the environment through judicious choices in synthetic routes and materials [1]. This literature review examines recent advances in green chemistry that contribute to sustainable industrial processes, exploring innovative methodologies, materials, and applications that align with these principles.

The fundamental concept of sustainability in chemical processes encompasses several key areas. The idea of a circular economy (CE) has gained significant ground over the past decade as a means of addressing sustainable development and circumventing the limitations of current linear production and consumption patterns. A primary goal of CE is to encourage closing-the-loop production methods to improve resource efficiency, modify chemical processes, and extend product and material lifespans [2]. According to the 2030 Agenda for Sustainable Development, which focuses on 17 Sustainable Development Goals (SDGs), 14 call for the appropriate application of green chemistry concepts. Green and sustainable chemistry could be key to unlocking the economic potential of the circular economy toward new product design and ultimately solving waste management problems by serving as the foundation for novel products made from renewable feedstocks designed to be reused, recycled, or recovered with minimum energy requirements [2].

The integration of green chemistry principles into industrial processes has become urgent in recent years. Given the urgency to combat climate change and ensure environmental sustainability, chemical and process industries must transition to net-zero emissions by addressing core areas of carbon emissions reduction, efficient energy use, and sustainable practices. This transition focuses on cutting-edge technologies such as biomass utilization, biotechnology applications, and waste management strategies that are key drivers of sustainability [3].

2. Advanced Synthesis Methods and Green Catalysis

2.1 C-H Activation and Metal Catalysis

A significant advancement in green chemistry has been the development of direct C-H bond functionalization methods. The direct activation and functionalization of C-H bonds, bypassing intermediate functional group installation, is inherently step and atom economic. However, numerous factors still hinder the sustainability of large-scale applications. Research areas seeking to overcome these sustainability challenges include the pursuit of abundant metal catalysts, avoidance of static directing groups, replacement of metal oxidants, and introduction of bioderived solvents [1]. Recent progress in aryl C-H borylation demonstrates the evolution from using precious metals like iridium to emerging 3d metal catalysts, highlighting a shift toward more sustainable approaches [1].

The development of green catalytic systems has focused on replacing precious metals with abundant alternatives and creating reusable catalysts. One innovative approach involves using cellulose, a green and readily available phytochemical, immobilized on magnetite nanoparticles and doped with imidazole and cobalt complexes to create water-dispersible, recyclable, and efficient nanocatalysts for C-C cross-coupling reactions including fluoride-free Hiyama and Suzuki reactions in aqueous medium. The presence of imidazole with hydrophilic character on these cobalt complexes provides improved dispersion of catalyst particles in water, leading to both higher catalytic performance and facile catalyst recovery and reuse up to six times through magnetic separation [4]. These catalysts have demonstrated high activity and excellent efficiency for both Suzuki (80-98% yield; E factor: 1.1-1.9) and Hiyama (87-98% yield; E factor: 0.26-1.1) derivatives in short reaction times under mild conditions without hazardous materials. The lack of byproducts reflects high selectivity, and the lower E factor indicates more favourable processes from a green chemistry perspective [4].
Similarly, innovative approaches for C-C cross-coupling reactions have employed palladium nanoparticles: A green protocol for the in-situ synthesis of palladium nanoparticles on chitosan beads has been developed without toxic reducing agents, using a simple coordination reaction between prepared chitosan beads and palladium ions. The resulting catalysts have shown high activity in Suzuki-Miyaura cross-coupling and Heck reactions under greener conditions [5]. The bead form of these catalysts allows easy separation from reaction mixtures while maintaining catalytic activity and selectivity through multiple cycles, providing advantages for sustainable organic reactions through the use of biopolymer support [5].

2.2 Metal-Free and Biocatalytic Approaches

Metal-free synthesis methods represent another significant advancement in green chemistry. Conventional quinazoline synthesis methods often involve multistep reactions and require excess substrate amounts to control product selectivity, leading to significant resource wastage. From a green chemistry perspective, novel metal-free synthetic methods have been developed for 2-substituted quinazoline derivatives using 4,6-dihydroxysalicylic acid-catalyzed oxidative condensation of o-aminobenzylamines and benzylamines with atmospheric oxygen as the oxidant [6]. In these systems, catalytic amounts of $BF_3 \cdot Et_2O$ (10 mol%) as a Lewis acid successfully lead to efficient oxidative condensation and intramolecular cyclization with excellent atom economy and environmental factor. These methods have been expanded to gram-scale synthesis using salicylic acid as an organocatalyst, establishing practical green synthesis approaches for nitrogen-containing heterocycles that could contribute to pharmaceutical manufacturing and industrial applications [6].
Biocatalysis represents one of the most promising green chemistry approaches, particularly for pharmaceutical applications. Over recent decades, biocatalysis has gained growing interest for its potential to enable high efficiency, high yield, and eco-friendly processes aimed at producing pharmacologically relevant compounds. It has proven especially effective for preparing chiral molecules, with recent innovations in biotechnology and nanotechnology opening a new era of further developments in this field [7]. Enzymes offer several advantages as green tools, both in terms of catalysis and environmentally friendly reactions. The use of isolated enzymes from biological sources or whole-cell biocatalysts represents a valuable approach to obtaining pharmaceutical products. The sustainability, higher efficiency, and cost-effectiveness of biocatalytic reactions result in improved performance that can be translated from academia to industry [7].

2.3 Micellar Catalysis and Mechanochemistry

Novel catalytic environments have emerged as sustainable alternatives to traditional organic solvents. The twelve principles of green chemistry have established a framework for developing new processes or improving existing ones. In the field of organic synthesis, micellar catalysis has become a significant research area. This approach evaluates whether micellar catalysis meets green chemistry criteria by applying the twelve principles to micellar reaction media [8]. Many reactions can be transferred from organic solvents to micellar media, with surfactants playing a crucial role as solubilizers. This allows reactions to be conducted in a more environmentally friendly manner with reduced risk. Moreover, surfactants are being reformulated in their design, synthesis, and degradation to add advantages to micellar catalysis that align with all twelve principles of green chemistry [8].

Mechanochemistry represents another significant advance in green synthesis approaches. The development and broader adoption of new green methodologies for promoting sustainable development in chemistry laboratories and industry plays a significant role due to the economic importance of chemistry and its presence in everyday life. A sustainable approach to chemistry contributes to global well-being and complies with the United Nations Sustainable Development Goals and the European Green Deal. Both batch and continuous mechanochemical methods provide an eco-friendly approach for organic synthesis, with a lower environmental footprint in most cases compared to solution-based procedures [9]. This assessment is objectively based on the use of green metrics (e.g., atom and real atom economy, E-factor, process mass intensity, material parameter recovery, Eco-scale) and indicators (e.g., DOZN tool and life cycle assessment studies). The absence of bulk solvents, precise control over stoichiometry, and more selective reactions enabling simplified work-up procedures are distinctive factors marking the superiority of mechanochemical processes over solution-based chemistry [9].

3. Sustainable Solvents and Extraction Techniques

3.1 Green Solvents and Alternatives to Traditional Media

The development of environmentally benign solvents represents a cornerstone of green chemistry. In sustainable chemistry, the use of green solvents is increasingly emerging for the optimization of more eco-friendly processes that aim for biocompatibility and recycling. The green solvent Cyrene, obtained from biomass via a two-step synthesis, is increasingly being introduced as a solvent of choice for green synthetic transformations and biomaterial production, thanks to its biocompatibility and non-toxic, non-mutagenic properties [10]. It has found applications in important organic reactions that could potentially lead to the formation of relevant chemical bonds in bioactive molecules. Additionally, Cyrene has been employed in the production of biomaterials, providing a comprehensive overview of its use in various chemical and materials science applications [10].

Water represents the ultimate green solvent for sustainable processes. Water-soluble metal complexes with Schiff base ligands are of great interest to green chemistry researchers due to their stability, cost-effectiveness, eco-friendliness, electron-donating ability, and various applications. These complexes demonstrate biological activities including anti-inflammatory, anticancer, antibacterial, antifungal, antioxidant, and DNA binding properties. In recent years, transition metal complexes have played significant roles in industrial processes such as hydrogenation, carbonylation, oxidation, reduction, epoxidation, hydrolysis, decomposition, and polymerization reactions [11]. However, their limited aqueous solubility may be a major limitation to potential catalytic, industrial, and clinical applications. In industrial catalytic processes, water can minimize the environmental impact of different reactions while enabling simple and complete separation. As a green solvent, water is flexible, non-toxic, safe, readily available, environmentally harmless, and inexpensive. Attaching different substituents to Schiff bases enhances water solubility and catalytic activity [11].

Supramolecular deep eutectic solvents (SDES) represent an emerging class of green solvents: Solvent selection is essential for industrial and analytical extraction processes to ensure environmental safety and neutrality. Nevertheless, toxic and hazardous solvents are often used due to cost-effectiveness and ready availability. In green chemistry, alternative solvents such as supramolecular deep eutectic solvents are gaining attention for their superior performance compared to traditional non-green solvents in certain applications [12]. These solvents have proven valuable for analytical and industrial liquid-liquid extraction processes, with applications in physicochemical properties, extraction conditions, capacity factor, enrichment factor, fuel desulfurization, extraction of biologically active compounds, lignin valorization, and sample preparation [12].

3.2 Advanced Extraction Technologies

Significant advancements have been made in sustainable extraction methods that reduce environmental impact while improving efficiency. Subcritical water, which refers to high-temperature and high-pressure water, possesses the unique characteristic of dramatically decreased polarity with increasing temperature. This allows subcritical water to behave similarly to methanol or ethanol, making it a green extraction fluid for various organic species [13]. Subcritical water extraction (SBWE) has been applied to a wide range of natural products from medicinal herbs, vegetables, fruits, food by-products, algae, shrubs, tea leaves, grains, and seeds. This technique has successfully extracted alkaloids, carbohydrates, essential oils, flavonoids, glycosides, lignans, organic acids, polyphenolics, quinones, steroids, and terpenes [13]. The major advantages of SBWE include water's non-toxicity, making it suitable for extracting edible materials, and the elimination of liquid waste disposal. Compared to organic solvents, subcritical water offers ecological, economic, and safety benefits, while its adjustable density, ion product, and dielectric constant enable class-selective extractions based on temperature—extracting polar compounds at lower temperatures and less polar ingredients at higher temperatures [13].

Ultrasound-assisted extraction (UAE) offers another environmentally friendly approach: Multiple extraction methods have been proposed for obtaining bioactive compounds from foods, ranging from conventional techniques like maceration or Soxhlet extraction to more innovative methods such as ultrasound-assisted extraction (UAE). UAE constitutes a novel method belonging to green chemistry that enables the extraction of

bioactive compounds with lower solvent and energy requirements while preserving molecular integrity [14]. In recent years, this method has been frequently used for extracting different bioactive compounds from various algae, especially polysaccharides like carrageenans and alginate; pigments including fucoxanthin, chlorophylls, or β-carotene; and phenolic compounds. The application of UAE to marine algae represents an efficient and sustainable strategy for deep characterization of new sources of bioactive compounds, especially suitable for vegetarian and vegan diets [14].
Recent advances in pectin extraction illustrate the evolution toward greener technologies: Pectin, a structural polysaccharide primarily consisting of galacturonic acid units, is conventionally extracted from agricultural waste (fruit and vegetable peels) using acidic or basic aqueous media at high temperatures. These processes are time- and energy-consuming and result in severe environmental problems due to acidic effluents and equipment corrosion. As pectin usage increases in food industries and pharmaceutical products, better extraction procedures are required to maximize yield and purity [15]. Various alternate green approaches for pectin extraction have emerged, including traditional acid extraction and emerging technologies such as deep eutectic solvent-based extraction, enzyme-assisted extraction, subcritical fluid extraction, ultrasound-assisted extraction, and microwave-based extraction. These methods aim to provide a platform for developing more efficient green methods for pectin extraction and its utilization for various biotechnological purposes [15].

4. Sustainable Materials and Functional Nanomaterials

4.1 Green Synthesis of Nanomaterials

The development of environmentally benign methods for synthesizing nanomaterials has become a priority in material science. Over the last two decades, oxide nanostructures have been continuously evaluated and applied in many technological applications. The advancement of controlled synthesis approaches to design desired morphologies is fundamental to material science and nanotechnology. While these nanostructures can be prepared via different physical and chemical methods, green and ecofriendly synthesis approaches offer promising ways to produce nanostructures with desired properties and less risk from hazardous chemicals [16]. Recent state-of-the-art advancements in green synthesis approaches for ZnO and TiO2 nanostructures have focused on routes such as solvothermal, hydrothermal, co-precipitation, and sol-gel methods using biological systems based on the principles of green chemistry [16].
Biological or green synthesis methods offer significant advantages over conventional approaches: Biological and green synthesis of nanomaterials is superior to chemical and physical methods due to nanoscale attributes implanted in a green chemistry matrix. This research investigates the growing relevance of nanocomposites manufactured using ecologically friendly, green technologies. The transition to green synthesis correlates with the worldwide drive for environmentally sound procedures, limiting the use of traditional harsh synthetic techniques [17]. The installation of green chemistry in synthesizing nanocomposites using plant extract matrices optimizes antibacterial characteristics, antioxidant properties, and biodegradability, helping to build sustainable green nanomaterials. Biologically friendly manganese-doped ZnO nanocomposites can help reduce the environmental impact of traditional materials. Based on these findings, it was determined that nanocomposites derived from biological resources should be produced on a wider scale to eradicate environmental and water contaminants through degradation [17].
Innovation in nanomaterial synthesis extends to carbon-based materials as well: Carbon quantum dots (CQDs), a new family of photoluminescent 0D nanoparticles, have recently received significant attention. They have enormous future potential due to their unique properties, including low toxicity, high conductivity, and biocompatibility, making them feasible replacements for conventional materials in various optoelectronic, biomedical, and energy applications [18]. Recent trends and advancements in synthesizing photoluminescent CQDs using environmentally friendly methods have focused on eco-friendly synthetic processes emphasizing biomass-derived precursors [18].

4.2 Bioinspired and Renewable Materials

Bioinspired approaches have emerged as promising strategies for sustainable materials: Global specialty silica production exceeds 3 million tonnes per annum with diverse applications across sectors and increasing demand for complex material structures and surface chemistries. Commercial manufacturing of high-value silica nanomaterials is energy and resource intensive. To meet market needs and mitigate environmental impacts, new synthesis methods for these porous materials are required. Bioinspired silica (BIS) provides a potential solution as a versatile and greener route with good scalability prospects, attractive process economics, and well-controlled product materials [19]. The potential of this system lies not only in providing specific lead materials but also as a rich design space for flexible and potentially predictive design of diverse sustainable silica nanomaterials. Realizing this potential requires an integrative mindset enabling parallel progression of multiple research strands according to needs, opportunities, and emergent knowledge. This specifically requires developing detailed understanding of material diversity and control, scale-up influences and mechanisms, and performance, economic, and environmental characteristics [19].

Renewable materials from biomass represent a crucial aspect of sustainable chemistry: In recent years, chemists have significantly changed their approach to synthesizing organic molecules in laboratories and industry. Researchers are encouraged to use "greener" reagents, solvents, and methodologies to address environmental concerns such as water, soil, and air pollution. The employment of plant and animal derivatives commonly regarded as "waste material" has paved the way for developing new green strategies [20]. Important innovations in this field include materials that have played crucial roles in organic reactions: wool, silk, and feather, along with proteins and their derivatives as supports and catalysts in green syntheses. Different materials have shown prominent activity in adsorbing metals and organic dyes, which has been a relevant focus over the past two decades, contributing to their potential future utilization [20].

The utilization of fungi for eco-friendly composite materials demonstrates innovative approaches to material design: The continually expanding use of plastic throughout our world, along with considerable increases in agricultural productivity, has resulted in a worrying increase in global waste and related environmental problems. The reuse and replacement of plastic with biomaterials, as well as the recycling of agricultural waste, are key components of a strategy to reduce plastic waste [21]. Saprobe fungi can convert agricultural waste into nutrients for their own growth and facilitate the creation of mycelium-based composites (MBC) through bio-fabrication processes. Different fungal species, substrates, and processing methods result in varying chemical, mechanical, physical, and biological properties that ultimately determine the functional aspects of the finished composites [21]. Over the last two decades, several innovative designs have produced a variety of MBC that can be applied across a range of industrial uses including packaging, household items, furniture, and building materials that can replace foams, plastics, and wood products. Materials developed from MBC can be considered highly functional, offering renewable and biodegradable benefits as promising alternatives to conventional materials [21].

5. Industrial Applications and Sector-Specific Advances

5.1 Pharmaceutical Industry

The pharmaceutical industry has seen significant advances in implementing green chemistry principles: The principles of green chemistry can be comprehensively implemented in the green synthesis of pharmaceuticals by choosing no solvents or green solvents (preferably water), alternative reaction media, and considering one-pot synthesis, multicomponent reactions, continuous processing, and process intensification approaches for atom economy and waste reduction. Green chemistry's execution in synthesis can be performed using a holistic design of the active pharmaceutical ingredient's life cycle, minimizing hazards and pollution, and maximizing resource efficiency [22]. Various approaches have been explored for implementing green chemistry principles in pharmaceutical synthesis, from raw materials to intermediates to final products, and scaling up to industry-based production. Case studies of established generic pharmaceuticals demonstrate how researchers and industries have thoughtfully implemented green synthesis processes to control atom economy and waste reduction to protect the environment. Significant reactions relevant for green synthesis, one-pot cascade synthesis, multicomponent reactions, continuous processing, and process intensification could contribute to the future of green and sustainable synthesis of active pharmaceutical ingredients [22].

Process mass intensity (PMI) metrics have provided valuable insights into the sustainability of pharmaceutical manufacturing: Peptide manufacturing is often limited to solid-phase peptide synthesis (SPPS), liquid phase peptide synthesis (LPPS), and to a lesser extent hybrid approaches, with SPPS emerging as the predominant platform technology. SPPS involves excessive solvents and reagents that negatively impact the environment, highlighting the need for newer technologies to reduce the environmental footprint [23]. Fourteen American Chemical Society Green Chemistry Institute Pharmaceutical Roundtable member companies compiled Process Mass Intensity (PMI) metrics to inform sustainability efforts in peptide synthesis, assessing 40 synthetic peptide processes at various development stages. This represents the most comprehensive assessment of synthetic peptide environmental metrics to date [23]. The peptide manufacturing process was divided into stages (synthesis, purification, isolation) to determine respective PMI values. On average, solid-phase peptide synthesis (PMI ≈ 13,000) does not compare favorably with other modalities such as small molecules (PMI median 168–308) and biopharmaceuticals (PMI ≈ 8300), warranting more environmentally friendly processes in peptide manufacturing [23].

5.2 Energy and Chemical Industry Transitions

The transition to sustainable energy production represents a critical application of green chemistry: Heterogeneous photocatalysis for water treatment and hydrogen production has gained interest among scientists and developers from different areas, such as environmental technology and material science. Most efforts and resources are devoted to developing new photocatalyst materials, while modeling and developing reaction systems for upscaling the process to pilot or industrial scale remain scarce [24]. Researchers have presented what is known about

upscaling heterogeneous photocatalysis for water purification and green hydrogen production, with case studies of reactors successfully used in water treatment plants. The challenges of upscaling photocatalysis for green hydrogen production are explored from the perspectives of reactor adaptation, process competitiveness, and safety considerations. Throughout this research, Green Chemistry and Engineering Principles are described and discussed regarding their current application to heterogeneous photocatalysis along with future challenges [24].
Chemical and process industries face unique challenges in implementing green chemistry principles: Specific industries such as cement manufacturing face unique challenges in reducing their carbon footprint, requiring innovative solutions. The role of hydrogen as a clean fuel is central to revolutionizing chemical and process sectors, pointing the way to cleaner and greener operations [3]. The European Green Deal and Sustainable Development Goals (SDGs) provide a clear roadmap and framework for advancing sustainability, driving innovation, and reducing the industry's environmental impact. Alignment with these initiatives can bring numerous benefits to the chemical industry, increasing competitiveness, promoting societal well-being, and supporting cross-sector collaboration to achieve shared sustainability goals [3].

5.3 Textile and Materials Manufacturing

The textile industry has benefited from innovative green chemistry approaches: The textile industry, a substantial component of the global economy, holds significant importance due to its environmental impacts. The use of water and chemicals during dyeing processes raises concerns about climate change and environmental sustainability. Hence, it is crucial for textile factories to adopt green industry standards, particularly in dyeing operations. Adapting to green industry practices aims to reduce water and energy consumption in textile dyeing processes, minimize waste, and decrease the carbon footprint [25]. Technological innovations have led to significant improvements in sustainability metrics. In one case study, a solar power plant was installed to optimize energy consumption, achieving 60% energy savings in summer and 25% in winter by 2023. Electricity consumption forecasting results have been essential for planning strategic initiatives to enhance factory efficiency. Improvements aimed at reducing energy consumption and lowering carbon footprints have led to optimizations in processes and layouts at specific bottleneck points, resulting in savings in labor, time, and space, and reduced unit production costs [25].
The wood industry demonstrates significant advancements in sustainable approaches: Wood is a renewable resource with excellent qualities and the potential to become a key element of a future bioeconomy. Increasing environmental awareness and sustainability goals are leading to a resurgence of research on wood materials. Nevertheless, global climate changes and associated consequences will soon challenge wood-value chains in several regions. To cope with these challenges, it is necessary to rethink current practices of wood sourcing and transformation [26]. Industrial processes have traditionally been optimized to suppress the variability of wood properties, enabling more efficient processing and reliable products. However, the need to preserve biodiversity and the impact of climate change on forests call for new wood processing techniques and green chemistry protocols for wood modification as enabling factors for managing a more diverse wood provision in the future [26]. Technological potentials of machine learning techniques and novel functional wood materials suggest that through a combination of sustainable forestry, adherence to green chemistry principles, and adapted processes based on machine learning, the wood industry could overcome current challenges and thrive despite future difficulties [26].

6. Assessment Metrics and Future Directions

6.1 Green Chemistry Metrics and Evaluation

The development of robust metrics for assessing green chemistry processes has become essential: The large and steadily growing demand for medicines combined with their inherently resource-intensive manufacturing necessitates sustainable production. However, the absence of clearly defined standards impedes pharmaceutical companies from performing reliable Life Cycle Assessments of their medicines and assessing the true value of their sustainable development achievements [27]. Guided by the UN Sustainable Development Goal 12, which aims to substantially reduce production waste by 2030, researchers have introduced improved metrics such as iGAL 2.0 alongside new Key Sustainability Indicators. These are based on improved statistical models that enable determination of meaningful API waste figures and early identification of potentially underperforming and environmentally concerning processes, delivering both environmental and economic value [27].
Standardized assessment approaches are critical for comparing different green chemistry methodologies: Green methodologies play a significant role in society due to the economic importance of chemistry and its widespread presence in everyday life. A sustainable approach to chemistry contributes to global well-being and complies with the United Nations Sustainable Development Goals and the European Green Deal. Assessment of green chemistry approaches is objectively based on metrics such as atom and real atom economy, E-factor, process mass intensity, material parameter recovery, Eco-scale, and stoichiometric factor [9].

6.2 Challenges and Future Research Directions

Despite significant advances, numerous challenges remain in implementing green chemistry at industrial scales: The integration of circular economy and green chemistry paradigms toward sustainable business models and new materials faces several challenges. This integration focuses on reducing waste, conserving resources, and minimizing negative environmental impacts while considering economic viability. However, obstacles to implementing CE and GC principles include investment requirements, environmental education needs, and legislative frameworks [2]. To advance toward a circular economy and green chemistry, international agreements should be reconsidered to provide an appropriate framework, including incentives for businesses and individuals to adopt circular practices, education programs to promote the benefits of circular practices, and regulations to support the transition to sustainable production and consumption patterns [2].

Innovative approaches are needed to address key limitations in current green chemistry applications: Our planet faces increasing entropy due to human activities such as overexploitation of natural resources and fossil fuel use. The COP28 in Dubai emphasized the urgency to abandon fossil fuels as the primary cause of human-induced environmental changes while highlighting the need to transition to renewable energies. Microbes play a crucial role in sustaining biogenic cycles to combat climate change, with synthetic biology tools showing economic potential for producing diverse non-fossil fuels and chemicals, contributing to emission reduction in transport and industry [28]. The shift to 'green chemistry' encounters challenges related to the availability of non-food residues and waste (mainly lignocellulosic) as raw materials, the construction of cost-effective bioprocessing plants, product recovery from fermentation broths, and the utilization of leftover lignin residues for synthesizing new chemicals, aligning with circular economy and sustainable development goals. To meet the Paris Agreement goals, an urgent global shift to low-carbon, renewable sources is imperative [28].

7. Conclusion

This literature review has examined recent advances in green chemistry for sustainable industrial processes, highlighting significant developments across multiple domains. From innovative catalytic systems and sustainable solvents to advanced extraction techniques and renewable materials, the field has demonstrated remarkable progress toward more environmentally benign chemical processes.

The integration of green chemistry principles with industrial applications has been particularly evident in pharmaceutical manufacturing, energy production, and materials science. Metrics for assessing the environmental impact of chemical processes have evolved to provide more accurate measures of sustainability, enabling researchers and industries to make informed decisions about process improvements.

Despite these advances, challenges remain in scaling up laboratory successes to industrial applications, addressing economic considerations, and developing comprehensive regulatory frameworks that incentivize green chemistry practices. Future research should focus on overcoming these challenges through interdisciplinary collaboration, continued innovation in catalysis and materials, and the development of more efficient and scalable processes that align with circular economy principles.

As global environmental concerns intensify and resource constraints become more pressing, green chemistry will continue to play a pivotal role in developing sustainable solutions that balance economic viability with environmental stewardship. The transition to greener industrial processes represents not only a scientific and technological challenge but also an opportunity to reimagine the relationship between chemistry, industry, and the environment for a more sustainable future.

References

1. Dalton, T., Faber, Teresa, and Glorius, F.. 2021. "C–H Activation: Toward Sustainability and Applications". ACS Central Science. https://doi.org/10.1021/acscentsci.0c01413
2. Ncube, A., Mtetwa, Sandile, Bukhari, Mahak, Fiorentino, G., and Passaro, R.. 2023. "Circular Economy and Green Chemistry: The Need for Radical Innovative Approaches in the Design for New Products". Energies. https://doi.org/10.3390/en16041752
3. Glavič, Peter, Pintarič, Z. N., Levičnik, Helena, Dragojlović, Vesna, and Bogataj, M.. 2023. "Transitioning towards Net-Zero Emissions in Chemical and Process Industries: A Holistic Perspective". Processes. https://doi.org/10.3390/pr11092647
4. Kargar, Pouya Ghamari and Bagherzade, G.. 2021. "A Green Synthesis Strategy of Binuclear Catalyst for the C-C Cross-Coupling Reactions in the Aqueous Medium: Hiyama and Suzuki–Miyaura Reactions as Case Studies". Frontiers in Chemistry. https://doi.org/10.3389/fchem.2021.747016
5. Oudghiri, Khaoula, Bahsis, Lahoucine, Eddarir, S., Anane, Hafid, and Taourirte, M.. 2023. "In Situ Decorated Palladium Nanoparticles on Chitosan Beads as a Catalyst for Coupling Reactions". Coatings. https://doi.org/10.3390/coatings13081367
6. Yamamoto, Yuki, Yamakawa, C., Nishimura, Riku, Dong, Chun-ping, Kodama, S., Nomoto, A., Ueshima, M., and Ogawa, A.. 2022. "Metal-Free Synthesis of 2-Substituted Quinazolines via Green

Oxidation of o-Aminobenzylamines: Practical Construction of N-Containing Heterocycles Based on a Salicylic Acid-Catalyzed Oxidation System". Frontiers in Chemistry. https://doi.org/10.3389/fchem.2021.822841

7. Rossino, Giacomo, Robescu, M. S., Licastro, Ester, Tedesco, Claudia, Martello, Ilaria, Maffei, Luciana, Vincenti, Gregory, Bavaro, T., and Collina, S.. 2022. "Biocatalysis: A smart and green tool for the preparation of chiral drugs". Chirality. https://doi.org/10.1002/chir.23498
8. Fabris, F., Illner, M., Repke, J., Scarso, A., and Schwarze, M.. 2023. "Is Micellar Catalysis Green Chemistry?". Molecules. https://doi.org/10.3390/molecules28124809
9. Fantozzi, Nicolas, Volle, Jean-Noël, Porcheddu, A., Virieux, D., García, Felipe, and Colacino, E.. 2023. "Green metrics in mechanochemistry.". Chemical Society Reviews. https://doi.org/10.1039/d2cs00997h
10. Citarella, A., Amenta, Arianna, Passarella, D., and Micale, N.. 2022. "Cyrene: A Green Solvent for the Synthesis of Bioactive Molecules and Functional Biomaterials". International Journal of Molecular Sciences. https://doi.org/10.3390/ijms232415960
11. Islam, M., Bitu, N. A., Chaki, B. M., Hossain, Md Jakir, Asraf, M., Hossen, M., Kudrat-E-Zahan, M., and Latif, Md Abdul. 2024. "Water-soluble Schiff base ligands and metal complexes: an overview considering green solvent". RSC Advances. https://doi.org/10.1039/d4ra04310c
12. Makoś-Chełstowska, Patrycja, Słupek, E., Fourmentin, Sophie, and Gębicki, Jacek. 2024. "Supramolecular deep eutectic solvents in extraction processes: a review". Environmental Chemistry Letters. https://doi.org/10.1007/s10311-024-01795-3
13. Cheng, Yan, Xue, F., Yu, Shuai, Du, Shichao, and Yang, Yu. 2021. "Subcritical Water Extraction of Natural Products". Molecules. https://doi.org/10.3390/molecules26134004
14. Carreira-Casais, A., Otero, P., García-Pérez, P., García-Oliveira, P., Pereira, A., Carpena, M., Soria-López, A., Simal-Gándara, J., and Prieto, M.. 2021. "Benefits and Drawbacks of Ultrasound-Assisted Extraction for the Recovery of Bioactive Compounds from Marine Algae". International Journal of Environmental Research and Public Health. https://doi.org/10.3390/ijerph18179153
15. Riyamol, Jeevitha, Chengaiyan, Gada, Singh, Sandeep, Ahmad, Faraz, Haque, Shafiul, and Çapanoğlu, E.. 2023. "Recent Advances in the Extraction of Pectin from Various Sources and Industrial Applications". ACS Omega. https://doi.org/10.1021/acsomega.3c04010
16. Gonçalves, R., Toledo, Rosimara P, Joshi, Nirav, and Berengue, O. M.. 2021. "Green Synthesis and Applications of ZnO and TiO2 Nanostructures". Molecules. https://doi.org/10.3390/molecules26082236
17. Hasan, Murtaza, Liu, Qian, Kanwal, Ayesha, Tariq, Tuba, Mustafa, Ghazala, Batool, Sana, and Ghorbanpour, M.. 2024. "A comparative study on green synthesis and characterization of Mn doped ZnO nanocomposite for antibacterial and photocatalytic applications". Scientific Reports. https://doi.org/10.1038/s41598-024-58393-0
18. Gulati, S., Baul, Arikta, Amar, Anoushka, Wadhwa, Rachit, Kumar, Sanjay, and Varma, R.. 2023. "Eco-Friendly and Sustainable Pathways to Photoluminescent Carbon Quantum Dots (CQDs)". Nanomaterials. https://doi.org/10.3390/nano13030554
19. Pilling, Robert J. and Patwardhan, Siddharth V.. 2022. "Recent Advances in Enabling Green Manufacture of Functional Nanomaterials: A Case Study of Bioinspired Silica". ACS Sustainable Chemistry and Engineering. https://doi.org/10.1021/acssuschemeng.2c02204
20. Casti, Federico, Basoccu, Francesco, Mocci, Rita, Luca, L. De, Porcheddu, A., and Cuccu, Federico. 2022. "Appealing Renewable Materials in Green Chemistry". Molecules. https://doi.org/10.3390/molecules27061988
21. Aiduang, Worawoot, Chanthaluck, Athip, Kumla, J., Jatuwong, Kritsana, Srinuanpan, S., Waroonkun, T., Oranratmanee, R., Lumyong, S., and Suwannarach, N.. 2022. "Amazing Fungi for Eco-Friendly Composite Materials: A Comprehensive Review". Journal of Fungi. https://doi.org/10.3390/jof8080842
22. Kar, S., Sanderson, H., Roy, K., Benfenati, E., and Leszczynski, J.. 2021. "Green Chemistry in the Synthesis of Pharmaceuticals.". Chemical Reviews. https://doi.org/10.1021/acs.chemrev.1c00631
23. Kekessie, Ivy, et al.. 2024. "Process Mass Intensity (PMI): A Holistic Analysis of Current Peptide Manufacturing Processes Informs Sustainability in Peptide Synthesis". Journal of Organic Chemistry. https://doi.org/10.1021/acs.joc.3c01494
24. Anaya-Rodríguez, Fernanda, Durán-Álvarez, J., Drisya, K., and Zanella, R.. 2023. "The Challenges of Integrating the Principles of Green Chemistry and Green Engineering to Heterogeneous Photocatalysis to Treat Water and Produce Green H2". Catalysts. https://doi.org/10.3390/catal13010154
25. Yılmaz, Kübra, Aksu, Inayet Ozge, Göçken, Mustafa, and Demirdelen, T.. 2024. "Sustainable Textile Manufacturing with Revolutionizing Textile Dyeing: Deep Learning-Based, for Energy Efficiency and Environmental-Impact Reduction, Pioneering Green Practices for a Sustainable Future". Sustainability. https://doi.org/10.3390/su16188152

26. Schubert, M., Panzarasa, G., and Burgert, I.. 2022. "Sustainability in Wood Products: A New Perspective for Handling Natural Diversity.". Chemical Reviews. https://doi.org/10.1021/acs.chemrev.2c00360
27. Roschangar, F., et al.. 2021. "Improved iGAL 2.0 Metric Empowers Pharmaceutical Scientists to Make Meaningful Contributions to United Nations Sustainable Development Goal 12". ACS Sustainable Chemistry and Engineering. https://doi.org/10.1021/acssuschemeng.1c01940
28. Ramos, Juan-Luis and Segura, Ana. 2024. "Microbial biotechnology and beyond: A roadmap for sustainable development and climate mitigation in the transition from fossil fuels to green chemistry". Microbial Biotechnology. https://doi.org/10.1111/1751-7915.14434