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Research Article

Advances in Ultrasound- and Plasma-Assisted Green Chemical Manufacturing: Process Intensification, Catalysis, and Sustainable Industrial Applications

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Abstract

The growing demand for sustainable and efficient chemical manufacturing has driven the exploration of advanced process intensification strategies, including ultrasound-assisted reactions, non-thermal plasma technologies, and hybrid catalytic systems. Ultrasound and plasma-based methodologies have demonstrated remarkable potential in reducing reaction times, enhancing selectivity, and lowering energy consumption in diverse chemical transformations. This review investigates the theoretical underpinnings, mechanistic pathways, and industrial implications of ultrasound- and plasma-assisted chemical processes, emphasizing their integration into green and continuous manufacturing paradigms. The study synthesizes experimental findings across multiple reaction types, including Suzuki–Miyaura cross-coupling, enzymatic transesterifications, bromination reactions, and ammonia synthesis. Special attention is devoted to process optimization approaches, including uniform design for ultrasound-assisted syntheses and reactor design for plasma-enhanced reforming technologies. The work further examines the synergistic interactions between ultrasound and catalysts, as well as the non-thermal plasma effects on molecular activation and pollutant abatement. Challenges such as scale-up limitations, energy efficiency, and mechanistic uncertainties are critically analyzed, highlighting future directions for the development of industrially viable, environmentally benign chemical processes. This comprehensive exploration underscores the potential of integrating ultrasound and plasma technologies into the fourth industrial revolution, facilitating sustainable production of pharmaceuticals, platform chemicals, and energy carriers while minimizing environmental impact.

Keywords: Ultrasound-assisted synthesis, non-thermal plasma, process intensification, green chemistry, continuous manufacturing, catalytic enhancement, sustainable chemical processes

INTRODUCTION

Modern chemical manufacturing is undergoing a profound transformation driven by environmental regulations, resource scarcity, and the need for energy-efficient, waste-minimized processes. Traditional chemical processes, often characterized by high energy consumption, excessive use of solvents, and generation of hazardous by-products, are increasingly incompatible with sustainability mandates (Mathiesen et al., 2023). In response, emerging technologies such as ultrasound-assisted chemical reactions and non-thermal plasma processes have gained prominence due to their capacity to intensify chemical transformations while adhering to green chemistry principles.

Ultrasound-assisted chemical synthesis relies on acoustic cavitation, the formation, growth, and implosive collapse of microbubbles in a liquid medium. This phenomenon generates localized hotspots with extreme temperatures and pressures, facilitating rapid mass transfer, enhanced mixing, and activation of chemical bonds (Hu et al., Miyaura cross-coupling catalyzed by Pd/PVP, has demonstrated accelerated reaction kinetics and higher product yields under mild conditions, thereby reducing environmental burden (De Souza et al., 2008). Beyond organometallic systems, ultrasound has proven effective in enzymatic transformations, including the synthesis of glycerol carbonate and esterification reactions, by improving substrate accessibility and enzyme–substrate interactions (Waghmare et al., 2015; Dange et al., 2015).

Complementing sonochemistry, non-thermal plasma technologies provide another avenue for sustainable process intensification. These plasmas operate under ambient or slightly elevated temperatures, generating high-energy electrons capable of inducing chemical reactions without bulk heating of the medium. Non-thermal plasma has been applied in pollutant abatement, hydrogen production, ammonia synthesis, and dry reforming of methane, demonstrating enhanced reaction rates and selectivity while minimizing energy input (Vandenbroucke et al., 2011; Abiev et al., 2020; Peng et al., 2018). The mechanisms underlying plasma-assisted processes involve the generation of reactive radicals, ions, and electronically excited species, which can activate otherwise inert molecules, expand reaction pathways, and enable catalytic synergy with heterogeneous catalysts (Kim et al., 2017).

Despite considerable progress, several challenges remain unaddressed in both ultrasound- and plasma-assisted chemistries. Key limitations include difficulties in scaling laboratory findings to industrial processes, energy efficiency optimization, mechanistic uncertainties, and the integration of these technologies into continuous manufacturing systems (Sagandira et al., 2022; Mehanna and Abla, 2022). Furthermore, the application of these methods to the production of high-value chemicals, such as succinic acid, polyols, and pharmaceutical intermediates, requires careful consideration of process control, reproducibility, and environmental safety (Kumar et al., 2024; Sardon et al., 2021; Vaidya et al., 2023).

This review aims to provide an in-depth, theory-driven synthesis of the current knowledge on ultrasound- and plasma-assisted chemical processes. By examining mechanistic insights, process optimization strategies, and industrial applicability, this work seeks to establish a framework for the development of next-generation, sustainable chemical manufacturing platforms.

METHODOLOGY

The methodology employed in this study involves a detailed synthesis of the literature on ultrasound- and plasma-assisted chemical transformations, integrating findings from experimental, theoretical, and computational studies. Ultrasound-assisted processes are analyzed through the lens of cavitation theory, sonochemical kinetics, and enzyme–substrate interactions. Critical parameters such as frequency, amplitude, temperature, solvent effects, and catalyst loading are discussed in relation to reaction efficiency and selectivity (Li et al., 2014; Lévêque et al., 2011). Special attention is given to uniform design optimization techniques, which allow systematic exploration of multivariable reaction spaces to identify conditions that maximize yield and minimize energy consumption (Li et al., 2014).

For plasma-assisted processes, non-thermal plasma generation mechanisms, reactor design considerations, and synergistic catalytic interactions are examined. Key variables such as discharge type (corona, dielectric barrier, arc), operating pressure, gas composition, and energy density are analyzed to elucidate their influence on reaction pathways and product distribution (Abiev et al., 2020; Peng et al., 2018; Petitpas et al., 2007). Comparative assessments of plasma-only versus plasma-catalyst hybrid systems provide insight into the mechanisms underlying enhanced reactivity and selectivity.

The methodology also includes an evaluation of process intensification approaches in continuous flow systems. Integration of ultrasound and plasma technologies into continuous reactors is discussed in terms of hydrodynamic considerations, mass and energy transfer optimization, and scalability to industrial production (Sagandira et al., 2022; Cespi, 2024). Lifecycle and environmental assessments are incorporated to contextualize the potential of these technologies in green and sustainable manufacturing frameworks (Mathiesen et al., 2023; Kumar et al., 2024).

RESULTS

Ultrasound-assisted chemical reactions consistently demonstrate marked improvements in reaction rates and selectivity. For example, the Pd/PVP-catalyzed Suzuki–Miyaura cross-coupling under microwave and ultrasound conditions exhibits near-complete conversion within significantly reduced reaction times compared to conventional thermal processes (De Souza et al., 2008). Similarly, ultrasound-assisted enzymatic synthesis of glycerol carbonate from glycerol and dimethyl carbonate achieves high yields due to improved mass transfer and substrate accessibility, highlighting the role of acoustic cavitation in overcoming diffusion-limited kinetics (Waghmare et al., 2015). Bromination reactions catalyzed by molybdenum complexes also benefit from secondary sonochemical effects, resulting in enhanced reaction efficiency under mild conditions (Lévêque et al., 2011).

Optimization studies employing uniform design approaches demonstrate that systematic variation of ultrasound parameters can fine-tune reaction outcomes. For instance, the synthesis of lutein disuccinate achieves optimal conversion by balancing ultrasound amplitude, reaction temperature, and substrate concentration, illustrating the importance of multidimensional process optimization (Li et al., 2014). Ultrasound-assisted esterification reactions, such as methyl butyrate formation using heterogeneous catalysts, further underscore the versatility of sonochemical methods in industrially relevant transformations (Dange et al., 2015).

Non-thermal plasma-assisted processes show comparable advantages, particularly in gas-phase and catalytic reactions. Hydrogen production via steam-oxidative reforming of bio-ethanol under Laval nozzle arc discharge conditions achieves high energy efficiency and selectivity due to the generation of reactive radicals that facilitate bond cleavage (Du et al., 2012). Dry reforming of methane using plasma-catalyst systems exhibits enhanced conversion and reduced carbon deposition, with synergistic effects arising from simultaneous thermal and non-thermal activation of reactants (Chung and Chang, 2016). Plasma-assisted ammonia synthesis over ruthenium catalysts demonstrates significant energy savings compared to traditional Haber–Bosch processes, highlighting the potential for plasma technologies to disrupt conventional industrial chemistry (Kim et al., 2017; Peng et al., 2018).

Beyond synthetic applications, ultrasound and plasma processes have proven effective in environmental remediation. Hydrodynamic cavitation combined with cold plasma facilitates degradation of pharmaceutical pollutants, such as furosemide, in aqueous environments, achieving high removal efficiency without the need for hazardous reagents (Verdini et al., 2024). These findings illustrate the broader applicability of these technologies beyond chemical manufacturing, extending to wastewater treatment and pollutant abatement.

DISCUSSION

The descriptive findings outlined above reveal several key insights regarding ultrasound- and plasma-assisted processes. Mechanistically, ultrasound enhances chemical reactions primarily through localized cavitation events that generate extreme microenvironments, promoting bond activation and mass transfer. These effects are particularly beneficial for heterogeneous and enzymatic reactions, where substrate accessibility and diffusion limitations often constrain reaction rates (Waghmare et al., 2015; Dange et al., 2015). However, the relationship between cavitation intensity and reaction outcome is highly nonlinear, necessitating precise control over ultrasound parameters to avoid undesirable side reactions or enzyme deactivation (Hu et al., 2025).

Plasma-assisted processes rely on high-energy electron interactions to initiate chemical transformations, often generating reactive radicals that facilitate otherwise kinetically challenging reactions. The coupling of plasma with heterogeneous catalysts produces synergistic effects, improving conversion and selectivity by combining thermal, electronic, and radical-mediated activation pathways (Chung and Chang, 2016; Abiev et al., 2020). Nevertheless, energy efficiency and scalability remain significant barriers, particularly in continuous industrial reactors where plasma uniformity and electrode design critically influence performance (Petitpas et al., 2007; Sagandira et al., 2022).

Integration of ultrasound and plasma technologies into continuous flow manufacturing represents a promising avenue for industrial application. Continuous reactors offer enhanced control over reaction residence time, temperature, and mass transfer, enabling the translation of laboratory-scale findings to commercial production of pharmaceuticals, platform chemicals, and bio-based materials (Vaidya et al., 2023; Kumar et al., 2024; Sardon et al., 2021). Moreover, these technologies align with the principles of the fourth industrial revolution by enabling real-time process monitoring, energy optimization, and automated control, contributing to more sustainable and resilient manufacturing systems (Mathiesen et al., 2023; Sagandira et al., 2022).

Despite these advantages, several challenges must be addressed to fully exploit ultrasound and plasma technologies. Scale-up remains a persistent issue due to the complex interactions between acoustic or plasma fields and fluid dynamics, which can lead to heterogeneous reaction environments. Energy consumption, particularly for plasma processes, must be optimized to ensure net environmental benefit. Additionally, the mechanistic understanding of radical generation, plasma–catalyst interactions, and cavitation-induced reaction pathways requires further investigation using computational modeling and in situ diagnostic tools (Peng et al., 2018; Verdini et al., 2024). Future research should also explore hybrid systems that combine ultrasound, plasma, and conventional catalytic methods, leveraging complementary activation modes to maximize efficiency and selectivity.

CONCLUSION

Ultrasound- and plasma-assisted technologies represent transformative approaches to sustainable chemical manufacturing, offering significant advantages in reaction rate, selectivity, and environmental compatibility. Ultrasound facilitates accelerated chemical and enzymatic transformations through cavitation-induced microenvironments, while non-thermal plasma provides high-energy electrons capable of initiating challenging chemical reactions. Both technologies demonstrate substantial potential for integration into continuous flow and green manufacturing paradigms, supporting the production of pharmaceuticals, bio-based chemicals, and energy carriers with reduced environmental footprint. Challenges related to scale-up, energy efficiency, and mechanistic understanding persist, but ongoing research into process optimization, hybrid activation methods, and real-time monitoring is poised to overcome these barriers. By leveraging the synergistic capabilities of ultrasound and plasma-assisted systems, the chemical industry can advance toward more sustainable, efficient, and resilient manufacturing models in line with the objectives of the fourth industrial revolution.

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