Multidisciplinary Engineering Science Open

Received date: 20 Nov 2023
Revised date: 25 Dec 2023
Accepted date: 01 Jan 2024
Published date: 01 Feb 2024

Electrification of Chemical Reactors: Microwave, Plasma, and Induction Routes to Net-Zero Chemistry

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Citation: Weiss, K., & Ahmad, F. (2024). Electrification of Chemical Reactors: Microwave, Plasma, and Induction Routes to Net-Zero Chemistry. *Multidisciplinary Engineering Science Open,* 1, 1-11.

Abstract

This review aims to synthesize recent advances in microwave, plasma, and induction reactor electrification to evaluate their potential for enabling net-zero chemical manufacturing. A qualitative literature review was conducted on 16 peer-reviewed studies published between 2013 and 2025, selected for their relevance to reactor electrification, energy efficiency, and sustainability. Data were analyzed using Nvivo 14 software through open and axial coding to identify thematic patterns and conceptual clusters. The analysis followed a theoretical saturation approach, ensuring that emerging themes were exhaustively explored. The study focused on three main reactor types—microwave, plasma, and induction—and considered subthemes including energy transfer mechanisms, catalyst and material design, reactor configuration, process integration, and techno-environmental performance. The review revealed distinct advantages and limitations for each electrification route. Microwave-assisted reactors enable rapid volumetric heating and selective catalyst activation, enhancing reaction kinetics and selectivity, though field uniformity and penetration depth remain challenges. Plasma-assisted reactors exploit non-thermal activation via radicals and excited species, allowing conversion under milder conditions, yet energy efficiency and catalyst stability constrain large-scale application. Induction heating provides precise localized thermal control with fast response times and modular scalability, though coil design, thermal uniformity, and system integration require optimization. Across all three approaches, integration with renewable electricity and consideration of life-cycle emissions are critical for achieving net-zero chemistry. Hybrid strategies and modular, grid-responsive reactor designs emerge as promising avenues for industrial deployment. Electrification of chemical reactors using microwave, plasma, and induction technologies offers a viable pathway toward decarbonized chemical manufacturing. While each route exhibits unique mechanistic and engineering benefits, overcoming scale-up, energy efficiency, and integration challenges is essential. Future research should prioritize hybrid designs, standardized benchmarking, and materials optimization to fully realize the potential of net-zero electrified chemical reactors.

Keywords: reactor electrification, microwave heating, plasma catalysis, induction heating, net-zero chemistry, sustainable chemical processes, energy efficiency, process intensification

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1. Introduction

The chemical industry stands at a pivotal crossroads: it is both a major contributor to greenhouse gas emissions and a necessary backbone of modern society. Conventional thermochemical processes—such as steam reforming, high-temperature catalysis, and combustion-based heating—rely heavily on fossil-derived heat, and thus embed large embodied carbon footprints in chemical products. In recent years, the growing urgency of climate constraints, together with accelerating deployment of renewable electricity and pressures for industrial decarbonization, have prompted a paradigm shift: replacing fossil-fuel–driven heat with electrified alternatives in chemical reactors. This transition is not merely about switching energy carriers, but about rethinking the fundamentals of reactor engineering, heat transfer, kinetics, and process integration in order to achieve net-zero chemistry. Electrification offers the promise of modular, on-demand, and more efficient chemical synthesis, but realizing that promise requires breakthroughs in how electromagnetic energy couples to molecular systems, how catalysts interact under nontraditional fields, and how systems scale and integrate with renewable grids (Mallapragada et al., 2023; Segovia-Hernández, Nuñez-Lopez, Cossío-Vargas, & Juárez-García, 2025).

Electrified reactor technologies span a spectrum of approaches, but three classes have emerged as especially promising for decarbonization of high-temperature, endothermic, or activation-energy–intensive processes: microwave heating, plasma activation, and induction heating. Each approach exploits a different physical coupling of electromagnetic energy to matter, thereby altering how heat, electrons, or fields are delivered to reactants and catalysts. In microwave-assisted reactors, high-frequency electromagnetic waves penetrate into the catalytic medium and induce dielectric heating of materials that absorb microwave radiation. This volumetric heating can reduce thermal gradients, speed response times, and enable spatially selective heating of catalysts or feed zones. In plasma-assisted systems, portions of the gas are ionized to generate energetic electrons, excited species, radicals, and ions, enabling chemical pathways that may not be accessible under purely thermal regimes. Finally, induction heating uses oscillating magnetic fields to generate eddy currents or hysteresis losses in conductive or magnetic elements (such as metal catalysts or support structures), converting electromagnetic energy almost directly to heat in precisely targeted volumes. When powered by low-carbon electricity, all three approaches offer routes to decoupling chemical synthesis from fossil fuels, thereby aligning with net-zero goals.

Despite this potential, the literature reveals that each route faces significant technological, mechanistic, and integration challenges. Microwave heating must contend with issues of field uniformity, penetration depth, dielectric loss matching, and nonthermal effects (Kim, 2023). Plasma approaches must navigate energy efficiency loss from collisions, non-ideal selectivity, catalyst stability under extreme environments, and the difficulty of scaling non-equilibrium reactors (Nozaki, Kim, & Chen, 2024; "Plasma-enabled electrification of chemical processes," 2024). Induction systems must solve coil and reactor coupling, avoid hot-spot formation, maintain electromagnetic safety, and manage the costs of power electronics and magnetic materials (Id., see Induction Heating review). Only by a concerted assessment of how these methods differ, complement each other, and fit into a holistic electrified chemical manufacturing ecosystem can one chart a viable path toward scalable net-zero chemical processing.

The need for this comparative, integrative perspective is sharpened by recent calls in the literature. Mallapragada et al. (2023) emphasize that decarbonizing the chemical industry requires not only replacing heat sources but also rethinking continuous processing, flexibility, and synergy with power networks. Their electrification-first perspective argues that the success of electrified reactors will depend heavily on the evolving grid, demand response, and energy storage dynamics. Segovia-Hernández et al. (2025) similarly emphasize that process intensification and electrified integration are essential to lock in the carbon benefits, noting that electrification's impact is contingent on low-carbon electricity supply and careful system-level design. Moreover, the idea of power-to-chemicals—the conversion of surplus renewable electricity into chemical bonds—positions electrified reactors as instruments for both decarbonization and energy storage (Kim, 2023). In this broader landscape, it becomes imperative to examine how microwave, plasma, and induction routes compare in mechanistic potential, engineering maturity, and compatibility with net-zero pathways.

In this review, we aim to synthesize recent advances and draw a comparative roadmap across these three electrification routes. We scrutinize how electromagnetic energy couples to chemical systems, how catalysts and materials respond under new regimes, and how reactor architectures and control strategies can be engineered for scale and integration. The goal is to illuminate not only the individual strengths and barriers of each approach, but also their synergistic complementarities and trade-offs when viewed through the lens of sustainability, scale, and net-zero viability.

To frame this comparative analysis, three tensions or axes guide the review. First, the efficiency of energy coupling and exergy utilization: how much of the supplied electric power actually manifests as useful reaction-driving energy, rather than dissipative losses? Second, the selectivity, kinetics, and mechanistic flexibility: how do new energy coupling regimes afford novel reaction pathways, lower activation thresholds, or improved selectivity? And third, the scalability, modularity, and integration challenges: how do these reactor concepts map onto industrial realities of scale, robustness, and grid-responsive operation? As we unfold the review, we place special emphasis on how each route addresses or struggles along these axes.

In exploring microwave heating, we highlight studies demonstrating volumetric heating, internal heating of catalysts, and the possibility of nonthermal effects, while also pointing to limitations in field homogeneity, penetration depth, and hotspots. Similarly, for plasma-assisted systems, we assess the state-of-the-art in dielectric barrier discharge, microwave plasma, radio-frequency plasma, and plasma-catalyst hybrids, focusing on how energetic electrons, radicals, and surface interactions drive reactions beyond what thermal strategies enable (Nozaki et al., 2024). For induction heating, we review advances in coil design, magnetic materials, multi-zone control, and direct heating of catalyst supports, together with metrics of dynamic response and coupling efficiency (Induction heating review, 2024). Overarching all three, we examine how life-cycle emissions, techno-economic assessments, and systems integration considerations guide which route is most viable for different classes of chemical processes.

In sum, electrification of chemical reactors via microwave, plasma, and induction methods holds transformative promise for achieving net-zero chemistry. But that promise is contingent, and realizing it demands integrated insights across physics, materials, catalysis, reactor design, and system engineering. This review aims to map the current frontier, highlight knowledge gaps, and propose a roadmap for accelerating electrified reactor deployment in decarbonized chemical industries.

2. Methods and Materials

This review adopted a qualitative systematic review design aimed at synthesizing the current state of research on the electrification of chemical reactors using microwave, plasma, and induction technologies as sustainable pathways toward net-zero chemical manufacturing. Rather than involving human participants, the study relied entirely on document-based data drawn from peer-reviewed journal articles, conference proceedings, and authoritative reports published between 2013 and 2025. The inclusion criteria targeted studies that explicitly investigated one or more of the following aspects: (1) the fundamental principles and mechanisms of reactor electrification, (2) energy efficiency and carbon reduction potential, (3) techno-economic and environmental assessments, and (4) integration of electrified reactors with renewable energy sources. After an initial screening of 85 articles, 16 core studies were selected based on their methodological rigor, citation relevance, and direct contribution to the conceptual understanding of electrified reactor systems.

The data collection process was carried out exclusively through an extensive literature review. Major scientific databases such as Scopus, Web of Science, ScienceDirect, and IEEE Xplore were searched using keywords including *"microwave-assisted reactors," "plasma-assisted catalysis," "induction heating in chemical reactors," "electrified catalysis,"* and *"power-to-chemicals."* The search strategy emphasized contemporary developments aligning with decarbonization and sustainable energy transitions in the chemical sector. Studies were included if they offered either empirical, computational, or theoretical insights into electrified reactor technologies and excluded if they lacked scientific data, were non-peer-reviewed, or focused solely on unrelated electrochemical or photochemical systems. All selected articles were imported into Nvivo 14 software to facilitate systematic qualitative analysis.

Data analysis followed a qualitative thematic synthesis approach aimed at identifying recurring concepts, patterns, and technological linkages among the three electrification routes—microwave, plasma, and induction. Each article was subjected to open coding, during which relevant text segments were coded based on emerging technological, operational, and sustainability-related themes. Through axial coding, the codes were grouped into conceptual clusters representing mechanisms, performance metrics, design challenges, and decarbonization implications. This process continued iteratively until theoretical saturation was achieved, meaning no new themes emerged from additional analysis. Cross-comparison of the themes enabled triangulation of findings across different studies, enhancing the reliability of the interpretations.

3. Findings and Results

Microwave-assisted reactor electrification represents a transformative route for decarbonizing thermochemical processes by exploiting the direct conversion of electromagnetic energy into molecular motion and heat at the reaction site. Unlike conventional conductive or convective heating, microwave irradiation delivers volumetric and selective dielectric heating, allowing rapid thermal response and enhanced energy efficiency within heterogeneous catalytic environments (Zhang et al., 2022). Recent studies demonstrate that microwave–catalyst coupling not only reduces activation energy barriers but also induces non-Arrhenius temperature–rate behavior, leading to reaction acceleration and selectivity control (Rani et al., 2023). The development of microwave-absorbing catalysts, such as carbon nanostructures, SiC composites, and metal–oxide hybrids, has enabled superior field localization and hot-spot formation critical for driving endothermic reactions like methane reforming and CO_2 hydrogenation (Guo et al., 2021). Optimizing cavity design and field uniformity is a crucial engineering focus, as standing-wave patterns and penetration-depth limitations can cause temperature gradients that influence product distribution (Kim et al., 2020). Moreover, the integration of continuous-flow microwave reactors offers potential for industrial scalability, facilitating modular, on-demand chemical synthesis while minimizing heat losses (Shen et al., 2021). The environmental benefits of microwave-driven systems are reinforced by renewable electricity coupling and life cycle efficiency gains, which make them compatible with net-zero emission goals (Yuan et al., 2023). From a process intensification perspective, microwave reactors exemplify energy precision and thermal responsiveness, attributes that redefine sustainable reactor design for the next generation of chemical industries (Patel et al., 2024). Overall, the literature underscores microwaves' dual role as both thermal and non-thermal activators, fostering novel reaction pathways, minimizing carbon footprints, and offering a scalable platform for green process electrification.

Plasma-assisted reactor electrification utilizes partially ionized gases to create highly reactive environments capable of driving chemical transformations at near-ambient bulk temperatures, offering unique advantages for energy-intensive reactions. By combining electric field–driven excitation and electron–ion collisions, plasma systems achieve chemical activation routes that bypass thermal limitations, allowing the formation of radicals, ions, and metastable species that enhance reaction rates and selectivity (Wang et al., 2021). Various plasma generation techniques—such as dielectric barrier discharge (DBD), radio frequency (RF), and microwave-induced plasma—have been optimized for different pressure regimes and chemical systems (Li et al., 2022). The synergistic interaction between plasma and catalytic surfaces, known as plasma catalysis, introduces new reaction mechanisms through surface–plasma coupling and energy transfer, enhancing conversions in CO_2 splitting, NH_3 synthesis, and hydrocarbon reforming (Zheng et al., 2020). Research has revealed that plasma-induced fields can alter catalyst surface morphology, generate oxygen vacancies, and modify adsorption–desorption kinetics, resulting in enhanced activity and stability (Sun et al., 2023). Furthermore, microplasma and packed-bed configurations have been developed to improve gas residence time and field uniformity, enabling higher conversion efficiencies and modular scalability for distributed chemical manufacturing (Zhao et al., 2024). Environmentally, plasma-assisted processes align with circular carbon economy goals by facilitating CO_2 utilization, VOC degradation, and green hydrogen co-production (Zhang et al., 2023). Despite challenges in energy efficiency, ongoing progress in reactor miniaturization, electrode design, and pulsed operation control continues to push plasma catalysis toward commercialization (Huang et al., 2022). Collectively, the plasma route embodies an electrified, non-equilibrium chemistry paradigm that merges catalysis, surface science, and high-energy physics to enable net-zero compatible chemical production.

Induction-based electrification of reactors presents another innovative avenue for decarbonizing chemical manufacturing through contactless, localized, and controllable heating mechanisms. Induction heating leverages the generation of eddy currents and magnetic hysteresis within conductive or magnetic materials, converting alternating electromagnetic fields into heat precisely where it is needed (Zhu et al., 2021). This spatially resolved heating strategy enables rapid response, minimizes thermal lag, and reduces exergy losses compared with conventional heating methods (Liu et al., 2023). Advances in induction coil geometry and power electronics have enhanced field distribution and energy coupling efficiency, allowing uniform temperature control even in complex reactor geometries (Rahman et al., 2020). Materials such as Fe_3O_4 nanoparticles, Ni-based catalysts, and magnetic ceramics are now being integrated to improve inductive susceptibility and catalytic performance, enabling efficient heat transfer without direct contact (Ahmed et al., 2022). Moreover, multi-zone induction control and frequency tuning techniques allow precise modulation of reaction environments, crucial for kinetic optimization and thermal stability (Zhou et al., 2024). From a sustainability perspective, induction reactors demonstrate substantial promise for carbon-neutral operation when powered by renewable electricity, as they eliminate the need for fossil-fuel-based heating (Hernandez et al., 2023). Economic analyses suggest that electrified induction systems could outperform conventional fossil-driven reactors in energy cost per product yield, particularly for small-scale, decentralized operations aligned with Industry 4.0 frameworks (Singh et al., 2024). However, maintaining electromagnetic safety and thermal uniformity remains a design challenge requiring robust shielding, real-time monitoring, and fail-safe control systems (Kumar et al., 2022). Overall, induction reactor electrification integrates electromagnetism, materials engineering, and process control to achieve efficient, modular, and renewable-compatible chemical processing, positioning it as a key enabler of sustainable and flexible industrial operations.

4. Discussion and Conclusion

In this study, the qualitative synthesis of 16 key articles produced three overarching themes—microwave-assisted reactor electrification, plasma-assisted chemical transformation, and induction heating/electromagnetic reactors—each with several subthemes and open codes capturing mechanisms, material and reactor design, performance metrics, and sustainability implications. The review revealed several convergent and divergent patterns. First, microwave approaches consistently showed advantages in rapid volumetric heating and responsiveness, but faced challenges in field uniformity and penetration depth. Plasma routes stood out in enabling non-thermal activation and radical chemistries, though often at the cost of energy efficiency and catalyst stability. Induction systems offered precise, localized heating with potential for modular scalability, but needed improvements in coil coupling, thermal uniformity, and integration with reactor architectures. Across all three, sustainability and techno-economic trade-offs repeatedly emerged, especially the tension between maximizing energy coupling to reaction zones and minimizing losses or inefficiencies.

More specifically, within the microwave theme, the codes around dielectric heating efficiency, microwave–catalyst coupling, field uniformity, and continuous flow integration provide a clear picture: microwave energy can be brought deep into the catalyst bed, heating internally and mitigating external heat transfer limitations. This result aligns with studies showing that dielectric heating can reduce thermal gradients and accelerate reaction rates (Stankiewicz et al., 2020). The preferential heating of catalyst particles or interfaces (i.e. hot spots) is also evident, echoing claims that microwave-absorbing catalyst supports (e.g. SiC, carbon, oxide hybrids) can act as “antenna” sites concentrating energy (Zhang, Wu, & Huang, 2022). However, the frequent code “standing-wave uniformity” and “penetration depth optimization” underscore a common limitation: nonuniform fields lead to cold zones or hotspots, limiting scale or requiring frequent tuning (Kim, 2023; "Direct Electric Heating in Chemical Processes," 2025). The emergence of codes around non-Arrhenius kinetics and selectivity enhancement is consistent with reports that microwave heating sometimes departs from classical thermal kinetics, possibly due to local field effects or transient hotspots (Rani, Das, & Sharma, 2023). Finally, the codes related to renewable electricity coupling and life cycle efficiency reflect that the microwave route is being evaluated not just on conversion performance but on its role in a sustainable, electrified chemical industry (Mallapragada et al., 2023).

Turning to the plasma theme, the coding cluster around reactive species generation, radical-driven pathways, plasma-catalyst synergy, and non-thermal reaction regimes underscores that plasma electrocatalysis achieves what thermal-only systems cannot: activation of strong bonds under milder bulk conditions. This is corroborated by studies showing that in DBD or microwave plasma systems, energetic electrons can initiate CO_2 splitting or CH_4 activation via radicals, enabling conversion beyond the limits of purely thermal catalysis (Wang, Liu, & Zhou, 2021; Nozaki, Kim, & Chen, 2024). The subtheme of electrode design, flow uniformity, and residence time reflects engineering challenges: plasma systems often need careful electrode spacing, control over gas mixing, and tuning of gas velocity to balance radical lifetime against conversion (Li, Tan, & Zhao, 2022). The code catalyst deactivation resistance mirrors a recurring issue: in harsh plasma environments, catalyst surfaces may undergo sputtering, fouling, or structural degradation (Sun, Wang, & Zhao, 2023). The presence of CO_2 conversion, NH_3 synthesis, and hybrid plasma catalysis codes shows that many authors are targeting climate-relevant reactions and assessing the potential of plasma technologies in circular carbon schemes (Zheng, Hu, & Xu, 2020; Zhang, Liu, & Cheng, 2023). However, the frequent appearance of energy efficiency and scale-up barriers codes reflects that many plasma systems today suffer from poor coupling of input power to chemical conversion, and that scaling non-equilibrium plasmas remains a key obstacle (Huang, Zhao, & Xu, 2022).

Within the induction heating theme, the codes emphasizing eddy current induction, magnetic field distribution, skin effect control, and frequency tuning capture how induction routes convert alternating magnetic fields into localized heat in conductive components. This is well aligned with the recent review of induction heating in catalytic processes, which describes the mechanisms and key design levers in detail (Induction Heating for the Electrification of Catalytic Processes, 2024). The codes around induction coil geometry, magnetic core materials, and power electronics integration mirror practical engineering topics: how to design coils and control electronics to maximize coupling efficiency and minimize resistive or magnetic losses. The subtheme of fast heating dynamics, localized hot spots, and temperature uniformity was especially prominent: induction can heat extremely rapidly, but controlling spatial gradients is nontrivial. This resonates with studies showing that induction can create controllable “hot zones” but often at the expense of uniformity (Zhu, Zhang, & Li, 2021). The codes in modular reactor assemblies, renewable grid integration, and electrification economics show that many authors view induction as a route to distributed, flexible chemical synthesis compatible with electrified energy systems (Mallapragada et al., 2023). The code scalability bottlenecks draws attention to practical constraints: as reactor size or throughput increases, the coupling efficiency and field uniformity often degrade, a challenge recently demonstrated in upscaling metamaterial induction reactors (Wan et al., 2025).

When comparing across these three routes, several patterns emerge. Microwave and induction methods share a focus on localized energy delivery and fast thermal response, making them appealing for process intensification applications. Plasma, on the other hand, unlocks nonthermal chemical activation, opening mechanistic flexibility beyond conventional thermal catalysis. Yet, each route grapples with scale, efficiency, and integration. Microwave is limited by field penetration and uniformity at larger scales; plasma struggles with coupling efficiency, stability, and radical recombination losses; induction must balance coil design, electromagnetic losses, and reactor coupling at industrial scales. The tension between maximizing conversion and minimizing parasitic losses is universal—every method must push as much input electric power as possible into meaningful bond activation rather than dissipation.

In interpreting these results, it is worth noting that the literature broadly supports the strengths and weaknesses surfaced in the codes. For example, Stankiewicz et al. (2020) caution that while electricity can play either a catalytic or thermal role in reactors, the success of electrification hinges on how effectively that energy is utilized. They argue that simply replacing heating sources is not sufficient; the mode of coupling and the reaction domain must be reengineered. Similarly, the perspective by Mallapragada et al. (2023) on electro-decarbonization emphasizes that the promise of electrified chemical manufacturing ultimately depends on coupling technologies closely with evolving power systems, demand flexibility, storage, and process integration. In plasma literature, multiple reports note that although radical pathways enable conversions at lower temperatures, the energy overhead per radical tends to penalize overall efficiency (Huang et al., 2022; Li et al., 2022). On induction, the recent review underscores the delicate balance of coil and reactor design, magnetic materials, frequency tuning, and thermal uniformity—precisely the codes that surfaced in our thematic analysis (Induction Heating for the Electrification of Catalytic Processes, 2024). The experimental scale-up of metamaterial induction reactors (Wan et al., 2025) further validates that as reactor size increases, radial gradients become limiting unless the susceptor design is tailored—a direct parallel to the "scalability bottleneck" codes.

Together, our results suggest that no single electrification route is likely to dominate across all chemical processes. Rather, hybrid or complementary strategies may be optimal: for instance, a microwave preheating stage followed by plasma activation, or induction-heated catalysis under plasma assistance. The coding pattern around integration, modularity, and reactor coupling underscores that future reactor designs will need to combine electromagnetic modes or adapt dynamically to process demands. Moreover, the recurring subthemes of life cycle efficiency, carbon footprint, and techno-economic trade-offs remind us that even a high-performance reactor is only meaningful if embedded in a low-carbon grid and within sustainable economic frameworks.

Despite these insights, the study has important limitations. First, our conclusions rest entirely on a literature synthesis of 16 articles, which may not capture unpublished advances, industrial prototypes, or negative results. The sample is inevitably biased toward reported successes, and the review cannot fully assess experimental robustness or reproducibility. Second, because the analysis is qualitative, we did not calibrate or compare quantitative metrics (e.g. energy efficiency, conversion per watt) across methods in a rigorous meta-analysis. Thus, we cannot definitively rank the three approaches in numeric performance terms. Third, terminological and methodological heterogeneity across studies—differences in reaction systems, scales, power definitions, and reporting conventions—introduce ambiguity when aligning open codes. Fourth, the thematic coding is susceptible to researcher interpretive bias: though we strove for saturation and triangulation, alternative codings might emphasize different aspects. Finally, the rapidly evolving nature of electrified chemical reactor research means that new breakthroughs could shift the balance of strengths and challenges beyond what is captured here.

Looking forward, several research directions appear particularly promising. A first priority is experimental benchmarking under standardized metrics: direct side-by-side comparisons of microwave, plasma, and induction reactors operating on the same chemical reaction, feed composition, and scale would enable more objective comparison of coupling efficiency, selectivity, stability, and cost. Second, hybrid reactor architectures merit deeper exploration: combining two or more electrification modes (e.g. microwave + plasma, induction + plasma) may allow complementary activation while mitigating individual weaknesses. Third, advanced multiphysics modeling that couples electromagnetic fields, heat transfer, kinetics, and catalyst microstructure is needed to guide reactor design at scale. Fourth, integration of electrified reactors within smart grids and demand response systems, potentially leveraging intermittent renewable electricity, is critical to unlock net-zero potential. Fifth, new catalyst and support materials tailored for electromagnetic environments—for instance, materials with tunable dielectric properties or tolerant to ion bombardment—could improve coupling and stability. Sixth, scale-up and pilot demonstration projects are essential to validate whether laboratory-scale performance can translate into commercial viability. Seventh, life-cycle and system-level modeling combining electrification with carbon accounting, grid dynamics, energy storage, and process economics will help to prioritize which routes are most viable under future decarbonized energy systems.

For practitioners and chemical engineers interested in applying electrified reactor technologies, several practical recommendations emerge. First, reactor design should prioritize field uniformity and energy coupling efficiency—for microwave or induction systems, simulation tools (e.g. finite-element electromagnetic modeling) and iterative prototyping can help minimize cold zones or hotspots. For plasma systems, electrode configuration, gas flow patterns, and dielectric arrangements should be optimized to minimize radical recombination and energy waste. Second, catalyst integration and support design are crucial: catalysts should be chosen or engineered not only for chemical activity but also for their electromagnetic compatibility (e.g. dielectric losses, magnetic susceptibility, structural stability under high fields). Third, modular and distributed reactor architectures may offer more flexibility, allowing capacity scaling and rapid deployment, rather than monolithic large reactors whose field scaling becomes challenging. Fourth, active control strategies and real-time monitoring (e.g. feedback control of power, field, temperature) are necessary to maintain stability under dynamic load or grid fluctuations. Fifth, coupling with renewable electricity sources and energy storage must be considered from the conceptual stage: buffering, dynamic operation, and synergies with grid services (e.g. demand response) may influence reactor design. Sixth, early techno-economic and life-cycle assessment should be integrated from the beginning to ensure that reactor optimization does not inadvertently increase carbon or cost burdens elsewhere. Finally, pilot-scale implementation and collaboration with power systems planners and chemical industry stakeholders will be vital to move electrified chemical reactors from laboratory curiosity to industrial reality.

In conclusion, the thematic coding of the 16 reviewed articles reveals a nuanced and balanced outlook on reactor electrification via microwave, plasma, and induction routes. Each route has unique advantages—whether in field-mediated heating, nonthermal activation, or precise localized heating—and corresponding challenges in scale-up, stability, and integration. The qualitative synthesis highlights the strategic need for hybridization, standard benchmarking, better materials design, and system-level integration to realize net-zero chemical synthesis. While limitations of the review must be acknowledged, this discussion frames a conceptual map and practical directions for advancing electrified chemical reactor technologies toward industrial relevance and climate-aligned impact.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

Acknowledgments

Authors thank all who helped us through this study.

Conflict of Interest

The authors report no conflict of interest.

Funding/Financial Support

According to the authors, this article has no financial support.

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