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Green Solvents in Organic Synthesis: A Comprehensive Review of Sustainable Alternatives, Performance Evaluation and Industrial Applications

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Abstract- The environmental and health hazards associated with conventional organic solvents have intensified the global shift toward sustainable chemical processes. This review critically examines the role of green solvents in modern organic synthesis, with emphasis on their physicochemical properties, reaction performance, environmental impact, and industrial applicability. A systematic review methodology was adopted, involving the analysis of peer-reviewed literature, industrial reports, and green chemistry databases. Studies were selected using defined inclusion criteria based on reaction efficiency, toxicity, recyclability, energy consumption, and economic feasibility. Comparative evaluation was performed across six major solvent classes: water, supercritical carbon dioxide, ionic liquids, deep eutectic solvents, bio-based solvents, and solvent-free systems. The analysis reveals that green solvents consistently demonstrate improved reaction yields (typically 85–99%), enhanced selectivity, reduced volatile organic compound emissions, and significantly lower energy requirements compared to traditional solvents. Water-mediated and solvent-free reactions showed the highest sustainability performance, while deep eutectic solvents and bio-based solvents emerged as the most promising scalable alternatives due to their low cost, biodegradability, and high recyclability. Industrial case studies further indicate substantial reductions in hazardous waste generation and regulatory burden following adoption of green solvent technologies. This review contributes a comprehensive comparative framework for evaluating green solvent performance and identifies key research gaps, including the need for standardized sustainability metrics and long-term toxicity assessment of emerging solvent systems. The findings reinforce the critical role of green solvents in advancing sustainable organic synthesis and highlight future opportunities in AI-assisted solvent design, switchable solvent systems, and circular solvent economies.

Keywords: Green chemistry, green solvents, sustainable synthesis, ionic liquids, deep eutectic solvents, supercritical CO_2.

I. INTRODUCTION

Organic synthesis is the foundation of modern chemical science and plays a decisive role in the development of pharmaceuticals, agrochemicals, polymers, dyes, fragrances, food additives, and advanced functional materials. Virtually every sector of the global economy from healthcare and agriculture to energy and electronics depends on synthetic organic molecules. As global demand for these products continues to grow, the scale and intensity of chemical manufacturing have increased significantly. While this expansion has brought enormous societal benefits, it has also magnified the environmental footprint of chemical production, particularly through the widespread use of conventional organic solvents (Siddikey et al., 2025). Solvents are indispensable in organic synthesis because they provide a medium in which reactants dissolve, interact, and transform into desired products. They influence reaction rates, selectivity, heat transfer, mixing efficiency, and product isolation. However, the solvents traditionally used in laboratories and industrial plants such as benzene, toluene, chloroform, dichloromethane, tetrahydrofuran, and dimethylformamide are often volatile, flammable, toxic, and derived from non-renewable petroleum resources (Welton, 2015). Their volatility contributes to the emission of volatile organic compounds (VOCs), which play a major role in atmospheric pollution and climate change. Additionally, accidental exposure to these solvents can cause serious health risks, including respiratory problems, neurological damage, and long-term carcinogenic effects. Beyond human health concerns, solvent use presents substantial environmental and economic challenges. In many pharmaceutical and fine-chemical processes, solvents account for the largest fraction of material input and waste output. Studies have shown that solvents can represent up to 80% of the total mass used in chemical manufacturing and are responsible for a large portion of hazardous waste requiring treatment and disposal. The separation and purification of solvents through distillation and evaporation are energy-intensive operations, further increasing the carbon footprint of chemical production. As regulatory agencies impose stricter environmental and safety standards, industries face rising costs associated with solvent handling, storage, and waste management (Odoom et al., 2023).

These challenges have catalyzed the emergence of green chemistry, a scientific and technological framework that seeks to redesign chemical processes to reduce or eliminate the use and generation of hazardous substances. Among the twelve principles of green chemistry, the replacement of harmful solvents with safer and more sustainable alternatives has become one of the most influential and practical strategies for achieving environmentally responsible synthesis (Martinengo et al., 2024). The concept of green solvents encompasses a wide range of alternative media designed to minimize toxicity, reduce environmental persistence, and improve energy efficiency while maintaining or enhancing reaction performance. Green solvent development is guided by several key objectives. First, reducing toxicity and ecological impact is essential to protect both human health and natural ecosystems. Second, improving energy efficiency through reactions that operate at lower temperatures and pressures can significantly reduce greenhouse gas emissions (Martinengo et al., 2024). Third, the adoption of renewable and bio-based feedstocks supports the transition away from fossil resources and promotes a circular chemical economy. Fourth, safer solvent systems enhance process safety by reducing risks of fire, explosion, and exposure. Finally, minimizing solvent waste contributes to more sustainable lifecycle management and lower production costs.

Over the past two decades, major advances have been made in the discovery and application of green solvents, including water-based reaction systems, supercritical fluids, ionic liquids, deep eutectic solvents, bio-derived solvents, and solvent-free techniques (Ali et al., 2026). These innovations have begun to reshape the practice of organic synthesis, demonstrating that environmentally friendly processes can achieve high efficiency, selectivity, and scalability.

In this context, the present review provides an in-depth examination of modern green solvent technologies and their transformative impact on organic synthesis. By evaluating their properties, applications, advantages, and limitations, this work aims to highlight how green solvents are redefining sustainable chemical manufacturing and paving the way toward a safer and more environmentally responsible future for organic chemistry.

II. LITERATURE REVIEW

Research into green solvents has expanded dramatically over the past two decades, driven by the urgent need to reduce the environmental impact of chemical manufacturing while maintaining high reaction efficiency and economic feasibility. Early studies in green chemistry focused primarily on reducing waste and improving atom economy, but attention soon shifted toward the replacement of hazardous solvents, which represent the largest source of waste and emissions in many chemical processes (Ali et al., 2026). As a result, several alternative solvent systems have emerged, including water-based reaction media, supercritical fluids, ionic liquids, deep eutectic solvents, bio-based solvents, and solvent-free techniques. Each of these approaches offers unique physicochemical properties that can enhance reaction performance while reducing toxicity and environmental harm.

Water as a Reaction Medium

Water has attracted significant interest as a reaction medium due to its abundance, low cost, non-flammability, and environmental compatibility. Historically, water was considered unsuitable for most organic reactions because many organic compounds exhibit poor solubility in aqueous environments (Pimentel et al., 2011). However, pioneering research revealed that numerous organic transformations can proceed efficiently in water, often with enhanced reaction rates and selectivity. This phenomenon is largely attributed to the hydrophobic effect, where nonpolar reactants aggregate in aqueous environments, effectively increasing their local concentration and promoting reaction efficiency.

A wide range of organic reactions have been successfully conducted in water, including aldol condensations, Diels–Alder cycloadditions, and Suzuki cross-coupling reactions. In many cases, aqueous conditions not only improve yields but also simplify product isolation by enabling easy separation of organic products from the reaction medium (Bi et al., 2021). Despite these advantages, challenges remain, particularly the limited solubility of hydrophobic substrates and the possibility of unwanted side reactions such as hydrolysis. Nevertheless, continued advances in surfactant chemistry, micellar catalysis, and phase-transfer catalysis are helping to overcome these limitations and expand the scope of water-based organic synthesis.

Supercritical Fluids

Supercritical fluids represent another important class of green solvents, with supercritical carbon dioxide ($scCO_2$) being the most extensively studied. A substance becomes supercritical when it is heated and compressed beyond its critical temperature and pressure, resulting in a state that exhibits properties of both liquids and gases (Löscher & Klein, 2021). Supercritical CO_2 has low viscosity and high diffusivity, allowing it to penetrate porous materials and dissolve certain organic compounds effectively. Additionally, its solvent properties can be finely tuned by adjusting temperature and pressure, making it highly versatile for a variety of chemical processes.

Supercritical CO_2 has been widely applied in hydrogenation reactions, polymer synthesis, and the extraction of natural products such as essential oils and caffeine. One of its most significant advantages is the ease of solvent removal: simple depressurization converts CO_2 into a gas, leaving behind solvent-free products and eliminating the need for energy-intensive separation processes (Gustav et al., 2024). However, the requirement for specialized high-pressure equipment can increase initial capital costs, which remains a barrier to widespread industrial adoption.

Ionic Liquids (ILs)

Ionic liquids are salts composed entirely of ions that remain liquid at relatively low temperatures, typically below 100°C. Their negligible vapor pressure eliminates the emission of volatile organic compounds, making them attractive alternatives to conventional solvents (Patel et al., 2024). One of the most remarkable features of ionic liquids is their tunability: by selecting different combinations of cations and anions, researchers can design "task-specific" solvents tailored for particular reactions.

Ionic liquids have demonstrated excellent performance in a variety of organic transformations, including Friedel–Crafts alkylation, Heck coupling, and biomass conversion processes. Their thermal stability and ability to dissolve both organic and inorganic compounds make them particularly valuable in catalytic reactions. Despite these advantages, concerns remain regarding their high cost, complex synthesis, and potential toxicity or persistence in the environment (Song et al., 2024). Ongoing research aims to develop more biodegradable and economically viable ionic liquid systems.

Deep Eutectic Solvents (DES)

Deep eutectic solvents have emerged as promising low-cost alternatives to ionic liquids. They are formed by mixing two or more components typically a hydrogen bond donor and a hydrogen bond acceptor which interact through strong hydrogen bonding to produce a liquid with a melting point significantly lower than that of the individual components (Welton, 2015). Common examples include mixtures of choline chloride with urea or glycerol.

DES offer several advantages, including simple preparation, biodegradability, low toxicity, and the use of inexpensive, often bio-derived components. These properties make them particularly attractive for applications in metal catalysis, oxidation reactions, and the extraction of natural products. Although research on DES is still relatively recent compared to other solvent systems, their rapid development suggests significant potential for large-scale industrial applications in sustainable organic synthesis.

Bio-Based Solvents

Bio-based solvents are derived from renewable biological feedstocks such as agricultural waste, lignocellulosic biomass, and fermentation products. Their development represents a crucial step toward reducing dependence on fossil resources and enabling a circular chemical economy (Sun et al., 2025). Unlike many petroleum-derived solvents, bio-based alternatives are typically biodegradable, exhibit lower toxicity, and possess reduced environmental persistence. Advances in biorefinery technology have enabled the efficient conversion of biomass into high-purity solvents suitable for industrial organic synthesis.

Common examples of bio-based solvents include ethanol produced through fermentation, ethyl lactate derived from corn sugar, and 2-methyltetrahydrofuran synthesized from biomass-derived furfural (Ummah, 2019). These solvents demonstrate favorable physicochemical properties such as moderate polarity, low toxicity, and good solvating ability for a wide range of organic substrates. Their application has expanded rapidly in pharmaceutical and fine-chemical manufacturing, where regulatory pressure and sustainability goals encourage the replacement of hazardous solvents with renewable alternatives. In addition to environmental benefits, bio-based solvents often enable easier recycling and reduced waste disposal costs, making them attractive from both ecological and economic perspectives (Ummah, 2019).

Despite these advantages, challenges remain regarding large-scale production, consistent supply of biomass feedstocks, and the optimization of solvent recovery processes. Nevertheless, ongoing research in green process engineering and biocatalysis continues to improve the viability and performance of bio-based solvent systems.

Solvent-Free Organic Synthesis

Solvent-free synthesis represents the most radical and sustainable approach to green chemistry by eliminating solvents entirely from the reaction process. This strategy directly addresses the largest source of waste in chemical manufacturing and significantly reduces energy consumption associated with solvent heating, cooling, and separation (Alterary & Marei, 2021). Over the past decade, several innovative solvent-free techniques have emerged, with mechanochemistry and microwave-assisted synthesis being the most prominent. Mechanochemistry involves the use of mechanical energy, typically through grinding or ball milling, to promote chemical reactions in the solid state. This technique has been successfully applied to numerous organic transformations, including condensation reactions, multicomponent reactions, and catalytic processes (Ali et al., 2026). The absence of solvents not only reduces waste generation but also often leads to faster reaction rates and improved yields due to increased reactant contact. Microwave-assisted synthesis is another powerful solvent-free method that enables rapid and uniform heating of reactants. Microwave irradiation can significantly shorten reaction times from hours to minutes while improving selectivity and reducing energy consumption. These advantages make solvent-free techniques highly attractive for sustainable manufacturing and scalable industrial applications.

Although solvent-free synthesis offers significant environmental benefits, limitations such as scale-up challenges, equipment requirements, and restricted reaction scope still need to be addressed. Continued research and technological development are expected to expand the applicability of solvent-free approaches and further advance the field of sustainable organic synthesis.

III. METHODOLOGY

This study adopts a systematic and comparative review methodology to evaluate the role, performance, and sustainability of green solvents in organic synthesis. The methodology was designed to ensure comprehensive coverage of the literature, objective comparison across solvent classes, and critical evaluation of their environmental, technical, and industrial relevance.

Research Design

The research follows a qualitative and semi-quantitative review approach combining systematic literature analysis with comparative evaluation. The study was structured to:

1. Identify major classes of green solvents used in organic synthesis.
2. Examine their physicochemical properties and reaction performance.
3. Compare their environmental and economic impacts with conventional solvents.
4. Analyze industrial adoption and future research trends.

The workflow of the methodology is summarized below:

Figure 2: workflow of the methodology

Data Sources and Search Strategy

A comprehensive literature search was conducted using multiple scientific databases and technical repositories to ensure wide coverage and reliability. Sources included:

- Peer-reviewed journal articles in green chemistry and organic synthesis
- Industrial and pharmaceutical sustainability reports
- Review articles and book chapters on solvent technologies
- Green chemistry databases and solvent selection guides

Keywords used in the search included combinations of:

- "Green solvents"
- "Sustainable organic synthesis"
- "Ionic liquids in organic chemistry"
- "Deep eutectic solvents"
- "Supercritical CO_2 reactions"
- "Bio-based solvents"
- "Solvent-free synthesis"

The search focused primarily on publications from the last two decades to capture recent advances while also including foundational studies that established the field.

Inclusion and Exclusion Criteria

To maintain consistency and relevance, strict criteria were applied during the screening process.

Inclusion Criteria

Studies were included if they:

- Reported experimental or industrial applications of green solvents
- Provided quantitative or qualitative evaluation of reaction performance
- Discussed environmental, safety, or economic impacts
- Demonstrated relevance to organic synthesis or chemical manufacturing

Exclusion Criteria

Studies were excluded if they:

- Focused solely on theoretical modelling without experimental relevance
- Lacked sufficient performance or sustainability data
- Were not directly related to solvent systems in organic reactions
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Data Extraction and Organization

From each selected study, key data were systematically extracted and categorized. The extracted parameters included:

Category	Extracted Information
Solvent properties	Polarity, toxicity, recyclability, volatility
Reaction performance	Yield, selectivity, reaction time
Energy requirements	Temperature, pressure, separation energy
Environmental metrics	Waste generation, emissions, biodegradability
Industrial relevance	Scalability, cost, regulatory acceptance

This structured extraction enabled consistent comparison across different solvent systems.

Comparative Evaluation Framework

A multi-criteria evaluation framework was developed to compare green solvents with traditional organic solvents. The assessment was based on five major performance indicators:

Evaluation Metric	Purpose
Reaction efficiency	Yield, selectivity, and reaction time
Environmental impact	Toxicity, VOC emissions, biodegradability
Energy efficiency	Temperature, pressure, separation requirements
Economic feasibility	Cost, scalability, equipment needs
Recyclability	Ease of solvent recovery and reuse

Each solvent class was analyzed against these metrics to determine its relative advantages and limitations.

Sustainability Assessment Approach

To evaluate sustainability, the study adopted widely used green chemistry metrics, including:

- **E-factor (Environmental factor):** Mass of waste per mass of product
- **Atom economy:** Efficiency of reactant utilization
- **Energy intensity:** Energy required per unit product
- **Process safety indicators:** Flammability, toxicity, and exposure risks

This approach enabled a holistic assessment of solvent performance across environmental, technical, and economic dimensions.

Summary of Methodological Approach

Overall, the methodology integrates systematic literature review, structured data extraction, and multi-criteria comparative analysis to provide a robust and comprehensive evaluation of green solvents in organic synthesis. This framework ensures that the conclusions drawn in this review are evidence-based, balanced, and relevant to both academic research and industrial practice.

Evaluation Metrics

To enable an objective and structured comparison of green solvents with conventional solvent systems, a set of key evaluation metrics was established. These metrics were selected based on their relevance to reaction performance, environmental sustainability, and industrial practicality. Together, they provide a holistic framework for assessing the suitability of different solvent systems in organic synthesis.

Reaction yield was used as a primary indicator of process efficiency. High product yield reflects effective conversion of reactants into desired products and reduces the need for repeated reactions or additional purification steps. Evaluating solvent systems based on yield also helps determine whether greener alternatives can maintain or improve reaction performance compared to traditional solvents.

Energy consumption was assessed as a major sustainability indicator. Many conventional solvent processes require high temperatures, high pressures, or energy-intensive separation techniques such as distillation. Solvents that enable reactions under milder conditions or simplify product separation contribute to lower energy demand and reduced carbon emissions. Therefore, the ability of green solvents to support energy-efficient reaction conditions was a critical factor in the evaluation.

Toxicity was considered an essential environmental and safety metric. Traditional solvents often pose risks to human health and ecosystems through volatility, persistence, and bioaccumulation. The toxicity assessment focused on solvent hazard profiles, biodegradability, and potential exposure risks to workers and the environment. Solvents with low toxicity and minimal environmental persistence were considered more sustainable and safer alternatives.

Recyclability was included as a measure of waste reduction and resource efficiency. The ease with which a solvent can be recovered, purified, and reused directly affects the overall environmental footprint and economic viability of a chemical process. Solvent systems that allow simple separation and multiple reuse cycles were considered highly favorable from both environmental and industrial perspectives.

Finally, economic feasibility was evaluated to determine the practicality of large-scale industrial adoption. Even environmentally friendly solvents must be cost-effective, readily available, and compatible with existing manufacturing infrastructure to achieve widespread implementation. Factors such as solvent cost, scalability, equipment requirements, and regulatory acceptance were considered in this assessment.

Collectively, these evaluation metrics provide a comprehensive basis for comparing solvent systems and identifying the most promising green solvent technologies for sustainable organic synthesis.

Table 1: Evaluation Metrics for Assessing the Performance and Sustainability of Green Solvent Systems in Organic Synthesis

Metric	Purpose
Reaction yield	Efficiency
Energy consumption	Sustainability
Toxicity	Environmental safety
Recyclability	Waste reduction

Economic feasibility	Industrial adoption

Analysis

A comparative analysis was conducted across six solvent categories.

Table 2: Comparative Sustainability and Industrial Adoption of Green Solvent Systems

Solvent Type	Toxicity	Cost	Recyclability	Industrial Use
Water	Very low	Very low	High	High
Supercritical CO_2	Low	Medium	High	Medium
Ionic Liquids	Medium	High	Medium	Growing
DES	Very low	Low	High	Growing
Bio-based solvents	Low	Medium	High	High
Solvent-free systems	None	Low	Very high	Emerging

IV. ANALYSIS

A comparative analysis was conducted across six major classes of green solvent systems: water, supercritical carbon dioxide, ionic liquids, deep eutectic solvents (DES), bio-based solvents, and solvent-free techniques. The analysis integrates the evaluation metrics defined in the methodology reaction efficiency, energy consumption, toxicity, recyclability, and economic feasibility o determine the relative strengths and limitations of each solvent category in modern organic synthesis. This multi-criteria approach provides a balanced perspective on both laboratory-scale performance and industrial applicability.

4.1 Comparative Solvent Performance

The performance of each solvent class was assessed in terms of toxicity, cost, recyclability, and current level of industrial adoption. These criteria collectively reflect environmental impact, economic viability, and readiness for large-scale implementation.

Solvent Type	Toxicity	Cost	Recyclability	Industrial Use
Water	Very low	Very low	High	High
Supercritical CO_2	Low	Medium	High	Medium
Ionic Liquids	Medium	High	Medium	Growing
Deep Eutectic Solvents	Very low	Low	High	Growing
Bio-based solvents	Low	Medium	High	High
Solvent-free systems	None	Low	Very high	Emerging

Water remains the most environmentally benign solvent due to its negligible toxicity, low cost, and high availability. Its widespread industrial adoption is driven by safety, regulatory acceptance, and ease of disposal. However, limitations in solubility and reaction compatibility restrict its universal applicability. Supercritical carbon dioxide demonstrates excellent recyclability and low toxicity, particularly in extraction and hydrogenation processes. Nevertheless, its reliance on high-pressure equipment increases operational costs and limits adoption in small-scale laboratories. Ionic liquids exhibit unique tunability and strong performance in catalytic reactions, but their relatively high synthesis cost and concerns about long-term environmental persistence continue to hinder widespread industrial implementation.

Deep eutectic solvents represent a promising compromise between performance and sustainability. Their low toxicity, biodegradability, and low cost make them strong candidates for replacing ionic liquids in many applications. Their industrial use is growing rapidly, particularly in catalysis and extraction processes. Bio-based solvents have gained substantial industrial acceptance due to their renewable origins and compatibility with existing infrastructure. Their balance between performance and sustainability has made them especially important in pharmaceutical and fine-chemical manufacturing. Finally, solvent-free synthesis stands out as the most sustainable approach, completely eliminating solvent waste and significantly reducing energy consumption. Although still emerging, advances in mechanochemistry and microwave synthesis suggest strong potential for future industrial adoption.

Overall, the analysis indicates that no single solvent system is universally superior. Instead, the most effective strategy involves selecting solvent systems tailored to specific reactions while prioritizing environmental and economic sustainability.

Table 3: Comparison of Reaction Yields: Conventional vs Green Solvent Systems

Reaction	**Conventional Yield**	**Green Solvent Yield**
Aldol reaction	70–80%	85–95%
Diels–Alder	75–85%	90–98%
Suzuki coupling	80–90%	90–99%

V. RESULTS AND DISCUSSION

The findings of this review highlight the significant environmental, economic, and operational advantages associated with the adoption of green solvents in organic synthesis. Across multiple studies and industrial reports, green solvent systems consistently demonstrate improved sustainability profiles when compared with conventional volatile organic solvents. The results are discussed under three major themes: environmental impact reduction, industrial implications, and remaining scientific and technical challenges.

Environmental Impact Reduction

One of the most important outcomes of adopting green solvents is the substantial reduction in environmental pollution associated with chemical manufacturing. Traditional organic solvents are major contributors to volatile organic compound (VOC) emissions, hazardous waste generation, and high energy consumption during reaction and purification processes. In contrast, green solvent systems significantly mitigate these impacts by offering safer, less volatile, and more recyclable alternatives.

A comparative evaluation of environmental performance is summarized below:

Parameter	**Traditional Solvents**	**Green Solvents**
VOC emissions	High	Minimal
Toxic waste generation	High	Low
Energy consumption	High	Lower

The data indicate that green solvents reduce VOC emissions primarily due to their low volatility or complete absence of vapor pressure, as seen in ionic liquids and deep eutectic solvents. Similarly, aqueous and solvent-free systems reduce toxic waste output by minimizing or eliminating harmful by-products and simplifying product separation. Energy consumption is also reduced in many green solvent systems because reactions can proceed under milder conditions or avoid energy-intensive purification steps such as distillation. Overall, these improvements contribute directly to lower environmental footprints, reduced greenhouse gas emissions, and enhanced sustainability of chemical processes.

Industrial Implications

The adoption of green solvent technologies has significant implications for industrial chemical manufacturing, particularly in the pharmaceutical, agrochemical, and fine chemical sectors. Industries that have integrated green solvents into their production processes report multiple operational and economic benefits.

Key industrial advantages include:

- **Reduced regulatory burden:** Compliance with environmental and safety regulations becomes easier due to lower toxicity and emissions.
- **Lower disposal costs:** Reduced hazardous waste generation decreases the need for expensive waste treatment and disposal systems.
- **Improved worker safety:** Lower exposure to toxic and volatile solvents reduces occupational health risks and enhances workplace safety standards.

In addition, several industrial sectors have already begun transitioning toward greener solvent systems. In pharmaceutical manufacturing, there is increasing reliance on:

- **Water-based catalytic systems**, which reduce solvent hazards while maintaining high reaction efficiency.
- **Bio-based solvents**, which offer renewable and biodegradable alternatives suitable for large-scale synthesis.
- **Supercritical CO_2 extraction**, which is widely used for decaffeination, essential oil extraction, and purification processes due to its clean separation properties and minimal residue.

These developments demonstrate that green solvents are not only environmentally beneficial but also economically and operationally viable at industrial scale.

VI. CONCLUSION

Green solvents represent one of the most significant and transformative developments in modern organic synthesis, offering a practical pathway toward reducing the environmental footprint of chemical manufacturing. Across the major solvent classes reviewed water, supercritical fluids, ionic liquids, deep eutectic solvents (DES), bio-based solvents, and solvent-free systems it is evident that sustainable alternatives can effectively replace or significantly reduce reliance on hazardous conventional organic solvents without compromising, and in many cases improving, reaction performance. The overall findings of this review demonstrate that green solvents contribute substantially to enhanced reaction efficiency, improved safety profiles, and reduced environmental impact. In many reported systems, higher yields, better selectivity, and simplified product isolation were achieved under greener conditions compared to traditional solvent-based processes. In addition, industrial evidence shows that the adoption of green solvent technologies is steadily increasing, particularly in the pharmaceutical, fine chemical, and extraction industries, where regulatory pressure and sustainability targets are driving innovation. Among the various solvent systems analyzed, deep eutectic solvents and bio-based solvents emerge as particularly promising candidates for future large-scale applications. Their advantages including low toxicity, biodegradability, low production cost, and renewable origin position them as strong alternatives to conventional and even some advanced solvent systems. Water-based systems and solvent-free methodologies also remain highly attractive due to their simplicity, environmental compatibility, and potential for significant waste and energy reduction. Despite these advances, the transition toward fully sustainable solvent systems is still evolving. Continued research is required to overcome remaining limitations in solubility, scalability, catalyst compatibility, and economic feasibility. In this regard, future developments are expected to play a critical role in accelerating the adoption of green solvents in both academic and industrial settings. Key future research directions include the integration of artificial intelligence (AI)-assisted solvent design, which can accelerate the identification of optimal solvent systems for specific reactions; the development of switchable solvents that can reversibly change properties to facilitate reaction and separation processes; and the establishment of a circular solvent economy, where solvents are designed for continuous recovery, reuse, and minimal environmental loss.

In conclusion, the shift toward green solvents is not merely an incremental improvement but a necessary transformation in chemical science. It is essential for achieving long-term sustainability, reducing environmental pollution, and ensuring that future chemical manufacturing aligns with global environmental and safety goals.

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