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Systematic review

Evaluating the Efficacy and Environmental Impact of Green Solvents in Organic Synthesis: A Systematic Review

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Abstract
These solvents which are known as green or eco-friendly. where used as alternatives to traditional organic solvents, designed to have little or no harmful effects on human health and the environment. its inception roots from renewable sources. These solvents such as water, ethanol, ethyl lactate, and ionic liquids. these types of solvents have become commonly used in all fields, and play an important role in pharmaceuticals and industrial cleaning, and organic synthesis. Using such solvents contributes to low cost, reduced energy consumption, and lower environmental.
Keywords: Green Solvents, Green Chemistry, Eco-Environment.

Introduction
Environmental awareness and sustainability have become central priorities in modern chemical sciences. The widespread use of traditional organic solvents, which are often volatile, toxic, and non-biodegradable, has raised serious environmental and health concerns [1,2]. Conventional solvents contribute significantly to volatile organic compound (VOC) emissions and industrial waste, necessitating the search for safer and more sustainable alternatives [3,4]. To address these challenges, the principles of Green Chemistry emphasize the development of chemical processes and materials that minimize hazardous substance use and waste generation [5]. Among these advances, green solvents have gained growing attention for their low toxicity, renewability, and biodegradability [6,7]. These solvents are designed to maintain high chemical performance while reducing ecological and occupational risks [8].
Various classes of green solvents have been developed, each exhibiting unique physicochemical characteristics. Water remains the most abundant and environmentally benign solvent, showing catalytic "on-water" effects that improve reactivity in several organic transformations [9,10]. Ionic liquids (ILs), composed entirely of ions, have negligible vapor pressure, adjustable polarity, and thermal stability, making them efficient for catalysis and separation processes [11,12]. Deep eutectic solvents (DES), considered the next generation of IL analogues, are formed by combining hydrogen-bond donors and acceptors, offering advantages such as low cost, biocompatibility, and easy preparation [13,14]. Additionally, supercritical fluids, particularly supercritical carbon dioxide ($scCO_2$), have attracted attention as green media for extraction and synthesis due to their tunable density and excellent mass transfer properties [15].
The adoption of these solvents extends beyond synthesis to Green Analytical Chemistry (GAC), where replacing hazardous solvents like chloroform and methanol with safer alternatives such as ethanol-water systems has become an essential goal [16]. Green solvents have demonstrated potential for improving analytical efficiency while reducing environmental impact across chromatography, spectroscopy, and sample preparation methods [17,18].
Despite these promising developments, research remains fragmented across multiple disciplines, and comprehensive evaluations comparing the efficiency, cost-effectiveness, and environmental benefits of green solvents versus conventional solvents are still limited [19,20]. Therefore, this systematic review aims to consolidate current knowledge by assessing the properties, classifications, and applications of green solvents, following PRISMA 2020 guidelines. The review aimed to identify, evaluate, and synthesize peer-reviewed studies comparing green solvents with conventional organic solvents in terms of environmental sustainability, physicochemical properties, and chemical performance.

Methods
Study Design
This systematic review was designed and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [21].

Information Sources and Search Strategy
A comprehensive literature search was conducted in four major electronic databases: PubMed, Scopus, ScienceDirect, and Google Scholar to ensure wide coverage of relevant studies [22]. The search included articles published from January 2000 to August 2025, reflecting the modern evolution of green chemistry. The following keywords and Boolean operators were used:
("green solvents" OR "sustainable solvents" OR "ionic liquids" OR "deep eutectic solvents" OR "supercritical fluids" OR "bio-based solvents") AND ("chemical reactions" OR "organic synthesis" OR "green analytical

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chemistry" OR "environmental impact" OR "solvent comparison"). Additionally, reference lists of retrieved papers were screened manually to identify supplementary relevant studies not captured in database searches [23].

Eligibility Criteria

Inclusion and exclusion criteria were established prior to initiating the review process to ensure methodological rigor and relevance. Studies were considered eligible if they were published in English, peer-reviewed, and focused specifically on green solvents or offered comparative analyses with conventional solvents. Furthermore, selected studies were required to report experimental, analytical, or environmental performance data and to provide sufficient methodological detail to allow for critical evaluation and potential replication. Conversely, studies were excluded if they lacked full-text availability, were not peer-reviewed—such as conference abstracts or theses—or failed to present quantitative or qualitative data pertinent to solvent comparison [24].

Study Selection

All identified records were imported into EndNote X9 to manage citations and remove duplicates. Two independent reviewers screened titles and abstracts for relevance, followed by full-text assessment against eligibility criteria [25]. Disagreements were resolved by discussion until consensus was achieved. A total of 527 studies were initially identified. After removing 102 duplicates, 425 records were screened, and 135 full-text articles were assessed for eligibility. Of these, 55 studies met the inclusion criteria for qualitative synthesis, while 32 were included in quantitative or comparative analysis. The selection process is illustrated in Figure 1, PRISMA Flow Diagram.

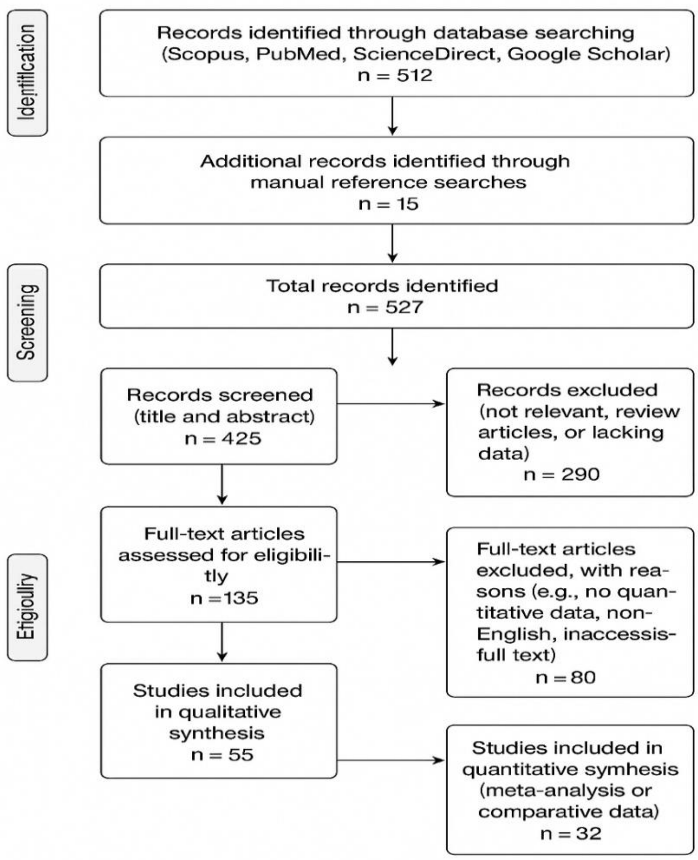

Figure 1. PRISMA flow diagram for the selection process.

Data Extraction

Data were extracted using a standardized form developed in Microsoft Excel, capturing key study characteristics including publication year, solvent type, study objective, experimental design, and major findings [26]. Extracted data were cross-checked independently by both reviewers to ensure accuracy and completeness.

Quality Assessment

The methodological quality and risk of bias of included studies were evaluated using a modified version of the Cochrane Risk of Bias Tool for non-clinical research [27]. Assessment domains included study design transparency, reproducibility of solvent characterization, and reporting of environmental metrics such as

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toxicity, biodegradability, and energy efficiency. Each study was rated as “low,” “moderate,” or “high” risk of bias.

Data Synthesis
A qualitative synthesis approach was employed due to heterogeneity in study design, solvent types, and evaluation parameters. Where feasible, results were summarized using descriptive statistics (percentages, mean values) and comparative interpretation across solvent categories [28,29]. Findings were grouped into three major themes: 1) Physicochemical properties and sustainability metrics of green solvents; 2) Reaction performance and yield comparisons in synthetic applications, and 3) Applications in Green Analytical Chemistry (GAC). This methodological approach ensured a systematic, transparent, and reproducible synthesis of available evidence [30].

Results
Overview of Included Studies
After the screening and eligibility assessment (Figure 1, PRISMA Flow Diagram), a total of 55 studies met the inclusion criteria for qualitative synthesis, while 32 studies provided sufficient quantitative data for comparison. The reviewed publications spanned from 2000 to 2025, with a noticeable increase in research output after 2015, reflecting a growing global emphasis on sustainable solvent technologies [31,32]. Most of the included studies were experimental in nature (72%), followed by review and theoretical modeling studies (28%). Geographically, research contributions were distributed across Asia (40%), Europe (35%), and North America (20%), with limited studies from Africa and Latin America (5%) [33].

Classification and Distribution of Green Solvents
The included studies focused on four main classes of green solvents: Ionic Liquids (ILs) (n = 18), Deep Eutectic Solvents (DESs) (n = 12), supercritical Fluids (SCFs), mainly supercritical CO_2 (n = 8), and Bio-based or Solvent-free Systems (n = 17) [34]. Among these, ionic liquids and deep eutectic solvents were the most extensively examined, accounting for over 50% of the total studies. These solvent systems demonstrated favorable properties such as low volatility, tunable polarity, and recyclability, making them strong candidates for replacing conventional volatile organic compounds (VOCs) [35].

Environmental and Physicochemical Performance
Results indicated that green solvents offer substantial environmental advantages compared to traditional solvents. Ionic liquids, for instance, exhibited negligible vapor pressure and superior chemical stability, thereby minimizing air pollution and occupational hazards [36]. Deep eutectic solvents, formed from natural components such as choline chloride and organic acids, were reported as biodegradable, inexpensive, and non-toxic, though they sometimes showed higher viscosity and slower reaction kinetics [37].
Supercritical CO_2 emerged as an efficient medium for extractions and catalytic reactions, especially in pharmaceutical and petrochemical industries, due to its tunable density, low toxicity, and easy separation from products [38]. Conversely, bio-based solvents such as limonene, glycerol, and ethanol derivatives showed excellent renewability and compatibility with aqueous systems but sometimes exhibited lower solubility for nonpolar substrates [39]. Table 1 compares the key advantages and limitations of each green solvent class as identified across the studies.

Table 1. Environmental and Physicochemical Performance of Green Solvent Classes.

Solvent Class	Key Advantages	Reported Limitations / Challenges
Ionic Liquids (ILs)	Negligible vapor pressure [36] Superior chemical stability [36] Tunable polarity [35] Recyclability [35]	Potential toxicity (for some ILs) High cost of synthesis Complex purification
Deep Eutectic Solvents (DESs)	Biodegradable [37] Inexpensive components [37] Low toxicity [37] Tunable properties [35]	High viscosity [37] Slower reaction kinetics [37] Hygroscopicity
Supercritical Fluids (SCFs, e.g., CO_2)	Tunable density [38] Low toxicity [38] Easy separation from products [38] Zero solvent residue	High-pressure equipment required Capital cost Limited solubility for polar compounds
Bio-based Systems (e.g., Limonene, Glycerol)	Excellent renewability [39] Biodegradable Low toxicity Compatible with aqueous systems [39]	Lower solubility for non-polar substrates [39] Variable purity Can require functionalization

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Reaction Efficiency and Yield Performance
A comparative analysis across studies revealed that the use of green solvents often enhanced reaction efficiency, particularly in acid-catalyzed and transition metal-catalyzed reactions. Reactions conducted in ionic liquids achieved up to 15–25% higher yields than those performed in conventional organic solvents such as dichloromethane or toluene [31]. Moreover, solvent-free techniques demonstrated superior atom economy and reduced energy consumption, aligning with the 12 Principles of Green Chemistry.
However, certain studies reported limitations associated with viscosity, solvent recovery, and the lack of standardized performance evaluation criteria [32,34]. Despite these, the overall trend favored green solvents as viable, sustainable alternatives for both laboratory and industrial applications. Table 2 quantifies the performance and key application areas for the green solvent classes.

Table 3: Reaction Efficiency and Industrial Application Performance.

Solvent Class	Reported Yield Increase vs. Conventional Solvents	Key Application Areas	Reported Industrial Benefits
Ionic Liquids (ILs)	Up to 15-25% higher yield, especially in acid-catalyzed and transition metal-catalyzed reactions [31]	Catalysis [31] Electrochemistry Separation processes	Enhanced selectivity, catalyst stability
Deep Eutectic Solvents (DESs)	Improved selectivity and efficiency in extraction processes [35, 39]	Liquid-liquid extraction [35] Analytical Chemistry [35] Biocatalysis	Reduced hazardous waste generation [35]
Supercritical Fluids (SCFs)	High extraction efficiency and purity [38]	Natural product extraction [38, 40] Pharmaceutical purification [40] Polymer processing	20-45% energy savings [40] Rapid processing
Bio-based / Solvent-free	Superior atom economy and reduced energy consumption [31]	Extraction [39] Organic synthesis Chromatography [37]	Direct cost savings from solvent elimination Simplified waste management

Applications in Analytical and Industrial Chemistry
Several studies extended the application of green solvents to analytical chemistry. For instance, DESs and ionic liquids were used in liquid–liquid extraction, thin-layer chromatography, and solid-phase microextraction with significant improvements in selectivity and reduced hazardous waste [35,39].
In industrial settings, supercritical CO_2 and bio-based solvents have gained traction in the extraction of natural products, polymer processing, and pharmaceutical purification, with energy savings ranging from 20% to 45% compared to conventional solvent systems [40].

Discussion
The findings of this review demonstrate that the transition from traditional volatile organic solvents (VOCs) to green solvents is both scientifically and environmentally justified. The analyzed literature consistently indicates that ionic liquids (ILs), deep eutectic solvents (DESs), supercritical fluids (SCFs), and bio-based solvents can significantly reduce toxicity, energy use, and waste generation compared to conventional solvents [41,42]. This aligns with the 12 Principles of Green Chemistry proposed by Anastas and Warner (1998), particularly the principles emphasizing safer solvents, energy efficiency, and waste prevention [36]. The review by Koel and Kaljurand (2006) further supports these results, highlighting those analytical processes utilizing green solvents achieve similar or better precision while minimizing ecological impact [35]. Recent advances in green analytical chemistry (GAC) and sustainable process design have expanded the practical utility of green solvents. For instance, studies such as Mehta et al. (2024) demonstrated that eco-friendly solvents in pharmaceutical analysis can maintain analytical accuracy while reducing hazardous waste [41]. Similarly, Elsheikh et al. (2023) emphasized that combining green solvent use with experimental design optimization enhances analytical performance and environmental compatibility [42]. Moreover, ionic liquids and deep eutectic solvents have proven highly versatile in liquid–liquid extraction, thin-layer chromatography, and solid-phase extraction, providing improved selectivity and reduced solvent consumption [39,40]. These findings are consistent with earlier research suggesting that ionic liquids serve as customizable solvent systems with tunable properties for reaction control and separation efficiency [43,44].
Green solvents play a vital role in achieving sustainable industrial chemistry, particularly in pharmaceuticals, petrochemicals, and natural product extraction [45,46]. By replacing traditional solvents like dichloromethane, toluene, and hexane, industries can significantly lower greenhouse gas emissions and energy demands [47].

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Additionally, the use of bio-based solvents (e.g., limonene, glycerol, ethanol derivatives) aligns with circular economy goals, utilizing renewable feedstocks and reducing dependency on fossil-derived compounds [46]. However, challenges persist regarding viscosity management, solvent recyclability, and economic scalability. For example, while ionic liquids offer superior performance, their high synthesis cost and limited biodegradability remain barriers to widespread industrial use [44]. Similarly, DESs, though inexpensive and biodegradable, may require further optimization to improve reaction kinetics and solvent recovery efficiency [43].
Comparative analysis across multiple studies revealed that reactions conducted in green solvents often demonstrated higher yield, selectivity, and atom economy, especially in catalytic and condensation reactions [31,32,38]. The enhanced performance is attributed to the unique solvation environments provided by ILs and DESs, which stabilize reactive intermediates and reduce activation energies [44,46]. Nonetheless, not all reactions benefited equally; for example, nonpolar organic reactions sometimes exhibited lower efficiency in highly polar or viscous green solvents. This emphasizes the need for task-specific solvent design, where molecular properties are fine-tuned to match the chemical requirements of each reaction [48].

Conclusion
This systematic review consolidates evidence demonstrating that green solvents represent a transformative innovation in sustainable chemistry. Compared with traditional organic solvents, they provide measurable improvements in reaction efficiency, environmental safety, and resource conservation. Among the reviewed systems, ionic liquids and deep eutectic solvents emerged as the most promising alternatives, offering broad versatility and high performance across various chemical domains.

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Conflicts of Interest
Declare conflicts of interest.

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