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Next Generation Solvents: A Sustainable Future with Green Chemistry Solvents

Yeni Nesil Çözücüler: Yeşil Kimya Çözücüleri ile Sürdürülebilir Bir Gelecek

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Next Generation Solvents: A Sustainable Future with Green Chemistry Solvents

ABSTRACT

Solvents are indispensable in industrial and consumer applications, yet conventional solvents, often comprising toxic volatile organic compounds (VOCs), pose significant risks to environmental and human health. The urgent need for sustainable alternatives has driven the development of green solvents, characterized by low toxicity, biodegradability, and alignment with green chemistry principles. This review conducts a comprehensive bibliometric analysis of 21.991 articles on green solvents published in the ScienceDirect database from 2010 to 2025, utilizing VOSviewer to map publication trends, journal distributions, subject areas, and keyword relationships. The analysis reveals a surge in publications since 2020, with approximately 80% of studies concentrated between 2010 and 2025, reflecting global sustainability priorities such as the UN Sustainable Development Goals and EU regulations on VOC emissions. This study critically synthesizes the literature, comparing green solvent types—water, supercritical fluids (CO_2 and ethanol), ionic liquids (ILs), deep eutectic solvents (DESs), and bio-based solvents—and their applications in chemical synthesis, pharmaceuticals, biotechnology, nanotechnology, and environmental remediation, including heavy metal and dye removal. By analyzing highly cited works and publication trends, it addresses the question: "What makes green solvents promising for sustainable chemical processes, and what barriers must be overcome to realize their full potential?" The review identifies key challenges, such as scalability, cost, and lifecycle impacts, and proposes targeted research directions, including lifecycle assessments (LCAs), interdisciplinary applications, hybrid solvent systems, and policy frameworks, to advance green solvent development and align with global sustainability goals.

Keywords- Bio-Based Solvents, Deep Eutectic Solvents, Ionic Liquids, Sustainability

Highlights

Green solvents, representing the next generation of sustainable chemical media, are pivotal for transforming industrial processes toward environmentally responsible and resource-efficient systems.

- A comprehensive bibliometric analysis of 21,991 studies (2010–2025) revealed a rapid surge in green solvent research since 2020, reflecting global alignment with sustainability policies such as the United Nations Sustainable Development Goals (UN SDGs) and the European Union Volatile Organic Compounds (EU VOC) regulations.
- Deep eutectic solvents (DESs) and bio-based solvents emerged as leading alternatives due to their biodegradability, low toxicity, and cost-effectiveness compared to ionic liquids (ILs).
- Despite promising laboratory performance, scalability, production cost, and lack of standardized lifecycle assessment (LCA) frameworks remain major barriers to industrial implementation.
- Future research should emphasize hybrid solvent systems, interdisciplinary applications, and policy mechanisms to accelerate large-scale adoption.

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ÖZ

Çözücüler, endüstriyel ve tüketici uygulamalarında temel bir rol oynar; ancak, genellikle toksik uçucu organik bileşikler (VOC'ler) içeren geleneksel çözücüler, çevre ve insan sağlığı üzerinde ciddi tehditler oluşturur. Sürdürülebilir alternatiflere yönelik acil ihtiyaç, düşük toksisite, biyolojik olarak parçalanabilirlik ve yeşil kimya prensipleriyle uyumlu yeşil çözücülerin geliştirilmesini hızlandırmıştır. Bu inceleme, 2010-2025 yılları arasında ScienceDirect veri tabanında yayımlanan 21.991 yeşil çözücü makalesine dayanan kapsamlı bir bibliyometrik analiz sunmakta ve VOSviewer aracılığıyla yayın eğilimlerini, dergi dağılımlarını, tematik alanları ve anahtar kelime bağlantılarını haritalandırmaktadır. Analiz, 2020'den itibaren yayınlarda belirgin bir artış olduğunu ve çalışmaların yaklaşık %80'inin 2020-2025 döneminde yoğunlaştığını göstermektedir; bu durum, BM Sürdürülebilir Kalkınma Hedefleri ve AB'nin VOC emisyonlarına yönelik düzenlemeleri gibi küresel sürdürülebilirlik öncelikleriyle uyumludur. Bu çalışma, literatürü eleştirel bir şekilde değerlendirerek yeşil çözücü türlerini—su, süperkritik sıvılar (CO_2 ve etanol), iyonik sıvılar (ILs), derin ötektik çözücüler (DESs) ve biyo-bazlı çözücüler—ve bunların kimyasal sentez, ilaç, biyoteknoloji, nanoteknoloji ve çevresel iyileştirme (ağır metal ve boya giderimi gibi) alanlarındaki uygulamalarını karşılaştırmaktadır. Yüksek atıf alan çalışmaları ve yayın eğilimlerini inceleyerek şu soruya yanıt aramaktadır: "Yeşil çözücüler, sürdürülebilir kimyasal süreçler için neden umut vericidir ve tam potansiyellerine ulaşmaları için hangi engeller aşılmalıdır?" İnceleme, ölçeklenebilirlik, maliyet ve yaşam döngüsü etkileri gibi temel zorlukları belirlemekte ve yeşil çözücü gelişimini ilerletmek ve küresel sürdürülebilirlik hedefleriyle uyumu güçlendirmek için yaşam döngüsü değerlendirmeleri (LCAs), disiplinler arası uygulamalar, hibrit çözücü sistemleri ve politika çerçeveleri gibi hedefe yönelik araştırma yönleri önermektedir.

Anahtar Kelimeler- Biyo-Bazlı Çözücüler, Derin Ötektik Çözücüler, İyonik Sıvılar, Sürdürülebilirlik

Öne Çıkanlar

Yeşil çözücüler, sürdürülebilir kimyasal ortamların yeni neslini temsil ederek endüstriyel süreçlerin çevresel açıdan sorumlu ve kaynak açısından verimli sistemlere dönüştürülmesinde kilit bir rol oynamaktadır.

- 2010–2025 yılları arasında yayımlanan 21.991 çalışmanın kapsamlı bir bibliyometrik analizi, 2020 yılından itibaren yeşil çözücüler üzerine yapılan araştırmalarda hızlı bir artış olduğunu ve bunun Birleşmiş Milletler Sürdürülebilir Kalkınma Hedefleri (UN SDGs) ile Avrupa Birliği Uçucu Organik Bileşikler (EU VOC) düzenlemeleri gibi sürdürülebilirlik politikalarıyla küresel düzeyde uyum gösterdiğini ortaya koymuştur.
- Derin ötektik çözücüler (DES'ler) ve biyo-bazlı çözücüler, iyonik sıvılara (IL'ler) kıyasla biyolojik olarak parçalanabilirlikleri, düşük toksisiteleri ve maliyet etkinlikleri nedeniyle öne çıkan başlıca alternatifler olarak belirlenmiştir.
- Laboratuvar ortamındaki umut verici performanslarına rağmen, ölçeklenebilirlik, üretim maliyeti ve standartlaştırılmış yaşam döngüsü değerlendirmesi (LCA) çerçevelerinin eksikliği, endüstriyel uygulamaların önündeki temel engeller olarak görülmektedir.
- Gelecekteki araştırmaların, hibrit çözücü sistemlerine, disiplinler arası uygulamalara ve büyük ölçekli uygulamaları hızlandıracak politika mekanizmalarına odaklanması önerilmektedir.

I.INTRODUCTION

Green chemistry, as defined by Anastas and Warner (1998) in Green Chemistry: Theory and Practice, aims to reduce environmental harm through 12 principles that prioritize resource efficiency, waste prevention, and the use of safer chemicals [1]. These principles align with global sustainability frameworks, such as the UN Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), which emphasize minimizing environmental footprints [2, 3]. Table 1 outlines the 12 principles of green chemistry as articulated by Anastas and Warner (2000), serving as the foundation for sustainable chemical processes [4]. These principles guide the development and assessment of green solvents by focusing on waste prevention, safer chemicals, and energy efficiency, providing a framework to evaluate their environmental and industrial feasibility across various applications.

Table 1. 12 rules of green chemistry [4].

Green chemistry rule	Explanation
1.Waste prevention	Preventing waste generation is a healthier option than cleaning it up after it has been generated.
2.Atom economy	Focuses on maximizing the use of raw materials in a chemical reaction.
3.Hazard free synthesis designs	The development of environmentally friendly synthesis pathways has increased in the last decade.

4.Production of safe chemicals	All physical and chemical hazards such as toxicity, explosiveness or flammability and the design of their processes must be addressed.
5.Safe solvents and additives	The solvent must be physically and chemically stable, have low evaporation properties, be easy to use and recyclable.
6.Design for energy efficiency	The design of chemical reactions that do not involve intensive energy use is extremely important.
7.Use of renewable sustainable raw materials	In the last decade, significant progress has been made in the production of fuels, chemicals and materials using renewable raw materials.
8.Reduction of derivatives	If possible, biological synthesis should be used.
9.Catalysis	In terms of environmental protection, the principle of catalysis encourages the use of biodegradable catalysts.
10.Design for biodegradation	The aim is to return as much waste as possible to production by using recycling and to prevent the formation of harmful substances.
11.Real time analysis for pollution	Green analytical chemistry can be defined as a field that involves the use of analytical procedures that produce less waste and are safer for the environment and human health.
12. Accident prevention and safe chemistry	Safety is defined as controlling known hazards and achieving an acceptable level of risk and is achieved at some level with minimal use of personal protective equipment.

Solvents, essential to chemical processes in industries such as pharmaceuticals and materials science, are a key focus for applying these principles. Conventional solvents, often volatile organic compounds (VOCs), significantly contribute to air pollution, carbon emissions, and biodiversity loss, necessitating the development of green solvents, including water, supercritical carbon dioxide (CO_2), supercritical ethanol, ionic liquids (ILs), and deep eutectic solvents (DESs) [3, 4]. These alternatives offer low toxicity, low volatility, and biodegradability, yet their adoption faces challenges related to scalability, cost-effectiveness, and performance compared to traditional solvents [3, 5].

The literature illustrates a complex interplay between theoretical advancements and practical challenges in green solvent development. Jessop (2011) establishes a foundational framework for assessing green solvents, emphasizing environmental impact, toxicity, and performance metrics, while noting trade-offs with industrial applicability [5]. Cvjetko Bubalo et al. (2015) advocate for deep eutectic solvents (DESs) over ionic liquids (ILs), citing simpler synthesis and lower costs, but highlight the absence of comprehensive life cycle assessments (LCAs) to confirm long-term sustainability [6]. Schuur et al. (2019) underscore the potential of green solvents in separation processes, yet point to economic barriers hindering large-scale adoption, particularly in industries reliant on established VOC-based processes [3]. Emerging applications, such as biosorption-based heavy metal removal and dye removal using green-synthesized nanomaterials, broaden the scope of green solvents in environmental remediation, aligning with green chemistry's waste prevention principles. These diverse perspectives underscore the need for a critical synthesis to compare solvent types, evaluate their contributions, and address gaps in scalability and sustainability.

This review utilizes bibliometric analysis with VOSviewer to investigate 21.991 articles from the ScienceDirect database (2010–2025), mapping publication trends, influential journals, subject areas, and keyword interconnections. Beyond data summarization, it critically assesses highly cited articles, evaluates publication trends, and synthesizes findings to address the core question: "What establishes green solvents as a cornerstone of sustainable chemistry, and what obstacles must be addressed to unlock their full potential?" The analysis incorporates emerging sources on biosorption, supercritical ethanol, and nanomaterial-based dye removal to expand the scope and strengthen thematic coherence. Detailed captions for figures and tables connect data to scientific and industrial contexts, enhancing interpretability. The review seeks to provide a comprehensive roadmap for advancing green solvent research by proposing strategies for scalability, interdisciplinary applications, and lifecycle sustainability.

II.METHOD

This study performed a bibliometric analysis of 21.991 green solvent-related articles published in the ScienceDirect database between 2010 and 2025. VOSviewer software was utilized to examine publication trends, journal distributions, subject areas, and keyword interconnections, with an emphasis on highly cited articles to evaluate their contributions, interrelations, and limitations. The analysis integrates quantitative trends (e.g., publication growth, journal prominence) with qualitative insights, critically comparing green solvent types (water, supercritical fluids, ionic liquids, deep eutectic solvents, and bio-based solvents) and assessing their environmental and industrial feasibility. The methodology prioritizes critical synthesis, addressing gaps in interdisciplinary research, lifecycle analysis, and practical implementation. Detailed captions for figures and tables provide scientific context, connecting data to trends, implications, and future research directions.

III.RESULTS AND DISCUSSION

Bibliometric analysis reveals that the Journal of Molecular Liquids is the predominant publication outlet for research on ionic liquids (ILs) and deep eutectic solvents (DESs), with 1.267 articles published between 2010 and 2025 (Table 2). This dominance reflects the journal's pivotal contribution to elucidating molecular-level interactions in solvent chemistry. However, the overwhelming concentration of publications in chemistry-centric journals underscores a notable lack of representation in interdisciplinary platforms. Such a limitation hinders the broader investigation and potential applications of these green solvents in fields like biotechnology, nanotechnology, and environmental remediation—areas where their low toxicity and sustainable properties could provide significant advantages, particularly in heavy metal and dye removal processes.

Table 2. Journals in which the articles were published (2010-2025)

Journals	Count
Journal of Molecular Liquids	1.267
Chemical Engineering Journal	475
Separation and Purification Technology	474
International Journal of Biological Macromolecules	425
Green Chemistry	394

A discernible increase in green solvent research has been observed over the past fifteen years, with 2024 representing the peak publication year within this period (Figure 1). This upward trajectory aligns with global sustainability initiatives, including EU regulations on VOC emissions and the UN Sustainable Development Goals, which prioritize environmental impact mitigation [2]. The growing demand from both governmental and industrial sectors for alternatives to conventional solvents has driven this policy-oriented research expansion.

However, the rapid proliferation of publications raises significant concerns regarding research quality and depth. While Jessop's (2011) seminal work established a comprehensive framework for evaluating green solvents based on environmental impact, toxicity, and performance parameters, contemporary studies predominantly focus on marginal improvements such as DES formulation optimization, often neglecting critical systemic challenges including scalability and lifecycle impacts [5]. Schuur et al. (2019) caution that despite demonstrating promising laboratory results, green solvents face substantial economic and infrastructural barriers in industrial applications [3]. This pattern suggests that recent publication growth may emphasize quantity over transformative innovation.

These trends underscore the pressing need for research that effectively bridges laboratory achievements with industrial implementation, while strategically leveraging policy frameworks to facilitate adoption. In emerging application domains such as wastewater treatment, future investigations should prioritize the development of scalable production methodologies and comprehensive life cycle assessments (LCAs) to ensure long-term sustainability and practical viability.

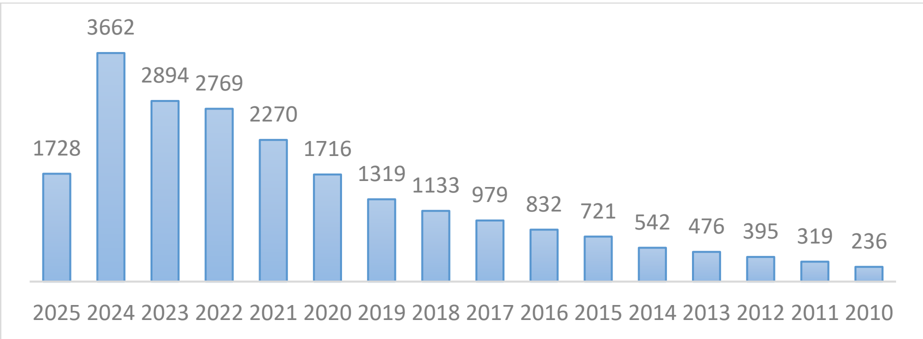

Figure 1. Annual distribution of publications (2010–2025)

Quantitative methods, which constitute approximately 50% of green solvent research (Figure 2), have proven effective for validating the catalytic performance of ionic liquids while simultaneously creating a significant research gap regarding the socio-economic and political factors influencing their industrial-scale implementation. Although studies such as Perna et al. (2020) successfully demonstrate the technical feasibility and economic advantages of deep eutectic solvents (DES) for industrial applications, they systematically fail to comprehensively examine the multidimensional relationships between technological performance, regulatory requirements, and market dynamics that ultimately determine commercial success [7]. Despite Jessop's (2011) proposal of comprehensive evaluation criteria integrating both technical and socio-economic parameters [5], this methodological gap persists, particularly in applied fields like wastewater treatment where interdisciplinary challenges are most pronounced. The integration of qualitative approaches - including stakeholder analyses and policy assessments - with existing performance metrics would establish a more robust foundation for both the scientific advancement and industrial applicability of sustainable solvent technologies.

Figure 2. Number of publications by article type

The analysis reveals a pronounced disciplinary concentration, with chemistry and chemical engineering collectively accounting for 75% of published articles (Figure 3). While this focused approach has facilitated substantial progress in solvent design principles, particularly for ionic liquids (ILs) and deep eutectic solvents (DESs) [6], it has concurrently limited the exploration of potential applications in adjacent fields including biotechnology, nanotechnology, and environmental remediation. This observation aligns with the foundational principles of green chemistry articulated by Anastas and Warner (2000), who emphasize that comprehensive sustainability solutions require cross-disciplinary integration [4]. Such an approach could catalyse transformative applications ranging from sustainable bioprocessing platforms to green nanomaterial synthesis, thereby directly contributing to the achievement of Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure). To maximize the societal and technological impact of green solvents, future research efforts should strategically target interdisciplinary publication venues and foster collaborative networks across traditionally distinct scientific domains.

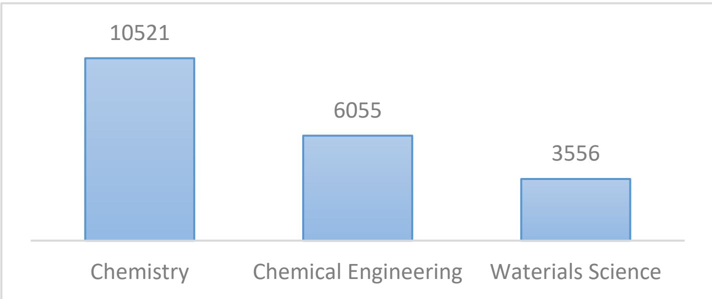

Figure 3. Number of publications related to green solvents in chemistry, chemical engineering, and materials science

The data reveal that over 75% of green solvent research originates from chemistry and chemical engineering disciplines (Figure 3). This finding indicates that research efforts have predominantly focused on molecular-level solvent design and optimization of physicochemical properties. However, this narrow focus has resulted in insufficient exploration of the unique advantages offered by green solvents in biotechnological processes, nanomaterial synthesis, and environmental remediation applications. Consequently, to maximize the impact of green solvent technologies in alignment with sustainable development goals, it is imperative to adopt interdisciplinary research paradigms and discover novel application areas consistent with green chemistry principles.

Bibliometric analysis reveals a predominant focus on technical disciplines such as chemistry, organic chemistry, materials science, and catalysis in green solvent research (Figure 4), while demonstrating that this narrow perspective systematically neglects critical sustainability dimensions. Keyword mapping studies (Figure 4) quantitatively confirm the inadequate representation of essential sustainability indicators, including lifecycle assessments and circular economy principles, within current research agendas. The limited presence of promising applications like dye removal using green-synthesized nanomaterials in the literature underscores the methodological imbalance resulting from the field's performance-oriented approach. Expanding interdisciplinary collaboration and routinely implementing lifecycle analyses would establish a more robust scientific foundation for the environmental claims of green solvent technologies. This comprehensive evaluation demonstrates that despite technical achievements in current research trends, deficiencies in sustainability considerations constrain the field's progress. For green solvents to be genuinely recognized as sustainable technologies, performance-focused approaches must be substantiated by comprehensive environmental and economic lifecycle assessments that validate their ecological and industrial viability.

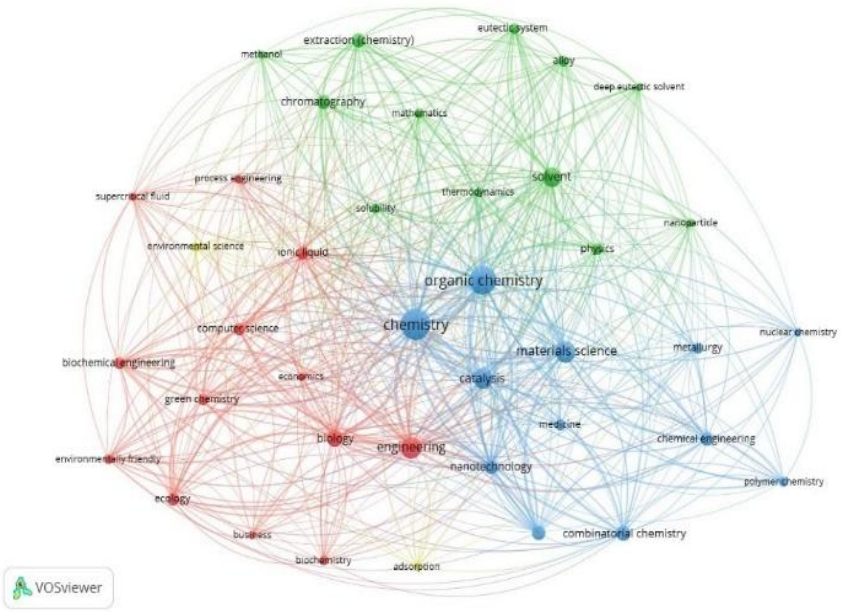

Figure 4. Keyword occurrences and total link strength

Table 3 presents the most influential publications in green solvent research, with Jessop's seminal 2011 work "Searching for Green Solvents" emerging as particularly noteworthy [5]. This foundational study established a comprehensive evaluation framework based on environmental impact, toxicity, and performance criteria, providing essential benchmarks for assessing green solvents across diverse applications ranging from catalysis to extraction processes. However, its predominant focus on theoretical parameters has resulted in limited consideration of practical industrial scalability factors. The 2020 study by Perna et al. addresses this limitation by demonstrating the superior cost-effectiveness and biodegradability of deep eutectic solvents (DES) compared to ionic liquids (ILs) [7]. Their research provides valuable insights into the practical implementation of green solvent technologies, particularly highlighting their potential in biocatalysis and extraction applications while bridging the gap between theoretical frameworks and real-world applications. Comparative analysis of these influential works reveals an evolving research trajectory from fundamental theoretical principles toward application-driven studies. Nevertheless, the persistent absence of standardized sustainability metrics continues to present a significant challenge in the field, underscoring the need for more comprehensive evaluation frameworks that encompass both theoretical and practical dimensions of green solvent development.

The article "Green solvents for green technologies" by Cvjetko Bubalo et al. (2015) examines environmentally benign solvents aligned with green chemistry principles [6]. It highlights ionic liquids, supercritical CO_2, subcritical water, deep eutectic solvents, and glycerol-derived solvents, which offer advantages such as low environmental impact, facile recovery, and energy efficiency. These solvents find applications in diverse industrial processes, including plastics and rubber production, wastewater treatment, and organic synthesis. However, the study identifies key limitations, notably the high cost of supercritical CO_2 extraction systems, insufficient toxicity data for certain solvents, and the absence of a universal protocol for solvent selection. The authors underscore the potential of green solvents in advancing sustainable technologies while emphasizing the need for comprehensive environmental and economic assessments to optimize their implementation.

Table 3. Key articles on green solvents and their citation impact

Article name	Year	Count of citations	Ref.
Searching for green solvents	2011	1.188	[5]
Green solvents for green technologies	2015	530	[6]
Deep eutectic solvents and their applications as green solvents	2020	434	[7]

IV.AREAS OF USE OF GREEN SOLVENTS

Green solvents are revolutionizing chemical processes by offering sustainable alternatives to traditional volatile organic compounds (VOCs), reducing environmental impact while maintaining efficiency. Water, supercritical fluids (e.g., supercritical CO_2 and ethanol), ionic liquids (ILs), and deep eutectic solvents (DESs) stand out for their low toxicity, recyclability, and alignment with green chemistry principles. These solvents are transforming fields from organic synthesis to food analysis, pharmaceutical production to textile dyeing. Yet, challenges like thermal stability, cost, and infrastructure demands limit their widespread adoption. Recent studies, such as those by Silva et al. (2025) and Thongolla et al. (2025), showcase the potential of green solvents and solvent-free methods, paving the way for a more sustainable future in chemistry [8, 9].

In organic synthesis, green solvents are critical for minimizing environmental harm. Lu et al. (2020) highlight the benefits of solvent-free and catalyst-free (SFCP) reactions, noting that green solvents like tetrahydrofuran (THF) and dimethyl sulfoxide (DMSO) deliver high regioselectivity and yields in reactions such as hydroboration, hydrophosphination, and click chemistry [10]. For example, in alkene hydroboration and hydrophosphination, THF and DMSO favor anti-Markovnikov products, while dichloromethane stifles the reaction. In Michael additions and multicomponent reactions, solvent-free conditions achieve 90–95% yields, whereas dichloromethane and DMF halt progress entirely. Click chemistry, including allene-azide reactions, yields excellent results with copper catalysts in green solvents [10]. Thongolla et al. (2025) push this further with a solvent-free N-Boc protection method for amines, using picric acid as an organocatalyst [9]. This approach yields 90% for 2-methylamine and works for both aromatic and aliphatic amines, eliminating solvent waste and aligning with green chemistry principles atom economy and safer solvents. This method offers a practical, eco-friendly solution for pharmaceutical and natural product synthesis.

In analytical chemistry, green solvents enhance sustainability in extraction and separation. Silva et al. (2025) developed a dispersive liquid-liquid microextraction (DLLME) method using green solvents to analyze carbonyl compounds in coffee extracts, key to flavor and aroma profiles [8]. By using minimal volumes of low-toxicity, biodegradable solvents, this method aligns with FDA guidelines for food analysis and achieves high sensitivity with reduced waste, embodying green chemistry principles #5 (safer solvents) and #6 (energy efficiency). Water, valued for its non-toxicity and cost-effectiveness, is widely used in normal-phase chromatography and biological applications, though its limited solubility for non-polar compounds poses challenges [7]. Supercritical CO_2 and ethanol, with their recyclability and tunable properties, excel in extraction processes like decaffeination and pharmaceutical isolation [8, 9]. The DLLME approach by Silva et al. (2025) complements these efforts, offering a sustainable tool for food quality control that could integrate with supercritical fluids or DESs for broader applications [8].

Ionic liquids (ILs) and deep eutectic solvents (DESs) are versatile, low-volatility options for catalysis, pharmaceutical synthesis, and battery electrolytes. ILs offer tunable chemical properties, but their synthesis from toxic precursors necessitates biodegradable variants [10]. DESs, with low toxicity and cost-effective synthesis, shine in biocatalysis and extraction but struggle with thermal stability at high temperatures [7]. Water-DES hybrids enhance solubility in complex syntheses, supporting sustainable pharmaceutical processes [8]. The solvent-free method by Thongolla et al. (2025) could inspire DES-based systems for amine protection, reducing environmental impact while maintaining high yields [9].

In pharmaceuticals, supercritical CO_2 and ethanol provide precise control for nanoparticle production and drug encapsulation, cutting VOC emissions [11]. However, their energy-intensive infrastructure limits adoption in cost-sensitive markets [11]. Metal-organic frameworks (MOFs) synthesized with water, supercritical CO_2, ILs, or DESs excel in applications like water purification, with ILs enabling 60–100% yields in palladium-catalyzed halosulfonylation, eliminating costly complexing agents [12]. The DLLME method by Silva et al. (2025) could verify the purity of MOF synthesis products, ensuring sustainability in analytical workflows [8].

Textile dyeing benefits from supercritical CO_2, which enables waterless dyeing with high color yield and washing fastness for polyester fibers, though it requires high-pressure equipment and is limited to specific fibers. Silicone-based solvents like decamethylcyclopentasiloxane (D5) offer anhydrous alternatives but face high costs and recovery challenges [13]. In recycling, the Solvent-Targeted Recovery and Precipitation (STRAP) method uses green solvents like cyclopentanone to selectively dissolve polymers (e.g., polyethylene, ethylene vinyl alcohol, polyethylene terephthalate), achieving 30 g/L solubility and superior life cycle assessment (LCA) results compared to toluene [13]. Toxicity and scalability issues, however, hinder food-grade recycling [13].

In electrospinning, green solvent systems like cyclopentanone/ethyl lactate/acetone and 1,3-dioxolane/ethyl lactate/acetone produce polylactic acid (PLA) nanofibers for air filtration, achieving 98% efficiency and 7–98 Pa pressure drops, replacing toxic dimethylformamide (DMF) [14]. Scalability and nanofiber crystallinity require further study [14]. The solvent-free approach by Thongolla et al. (2025) could inspire solvent-free electrospinning techniques, further reducing environmental impact. Microfluidic technologies amplify the efficiency of green solvents in catalytic processes, offering innovative solutions for natural product synthesis and industrial applications [9].

Green solvents and solvent-free methods, as exemplified by Silva et al. (2025) and Thongolla et al. (2025), are reshaping organic synthesis, analytical chemistry, pharmaceuticals, textiles, recycling, and electrospinning, as detailed in Table 4 [8, 9]. Challenges such as thermal stability, cost, and infrastructure needs persist, but hybrid solvent systems, renewable energy integration, and comprehensive LCA studies can bridge these gaps. These innovations highlight the power of green chemistry to create sustainable, efficient processes, driving chemistry toward a greener future.

Table 4. Green solvents and their application areas

Green solvent	Chemical formula	Areas of use	Properties	Ref.
DES	-	Chemical Synthesis, Bioengineering	Low toxicity, biodegradable	[2, 15]
IL	-	Polymerization, Chemical Synthesis	High solubility, low vapor pressure	[16]
Supercritical Carbon Dioxide	CO_2	Pharmaceutical Manufacturing, Extraction	Non-harmful, biodegradable solvents	[17]
Limonene (D-limonene)	$C_{10}H_{16}O$	Food and Pharmaceutical Industry	Safe, biodegradable, natural solvents	[18]
Ethyl Lactate	$C_6H_{12}O_3$	Food and Pharmaceutical Industry	Biodegradable, non-toxic, environmentally friendly	[19]
Propylene Carbonate (PC)	$C_4H_6O_3$	Painting, Coating, Solvent	Environmentally friendly, biodegradable	[20]
N-Methyl-2-Pyrrolidone (NMP)	C_5H_9NO	Pharmaceutical Manufacturing, Chemical Synthesis	High solubility, biodegradable	[21]
Tetrahydrofuran (THF)	C_4H_8O	Organic Chemistry, Nanotechnology	High solubility, low toxicity	[22]
Dimethyl Ether (DME)	C_2H_6O	Organic Synthesis, Nanotechnology	Low toxicity, high solubility	[23]
Glycerol	$C_3H_8O_3$	Pharmaceutical Manufacturing, Polymerization	High biocompatibility, non-toxic	[24]
Benzyl Alcohol	$C_6H_5CH_2OH$	Food and Pharmaceutical Industry	Environmentally friendly, biodegradable	[25]
Ethyl Acetate	$C_4H_8O_2$	Chemical Synthesis, Extraction	High solubility, biodegradable	[26]
Supercritical Methanol	CH_3OH	Biodiesel Production	High solubility, low environmental impact	[27]
Furfurol (Furfural)	$C_5H_4O_2$	Chemical Synthesis, Organic Chemistry	Low toxicity, biodegradable	[28]
Supercritical Ammonia	NH_3	Chemical Synthesis, Cleaning	High solubility, environmentally friendly	[29]
D-limonene	$C_{10}H_{16}O$	Food, Cosmetics, Cleaning	Natural, low toxicity, biodegradable	[30]
DES	-	Chemical Synthesis, Bioengineering	Low toxicity, biodegradable	[31]
IL	-	Polymerization, Chemical Synthesis	High solubility, low vapor pressure	[6]
Supercritical Carbon Dioxide	CO_2	Pharmaceutical Manufacturing, Extraction	Non-harmful, biodegradable solvents	[32]
Limonene (D-limonene)	$C_{10}H_{16}O$	Food and Pharmaceutical Industry	Safe, biodegradable, natural solvents	[33]

A. Potential and limitations of deep eutectic solvents for green and sustainable industrial

Deep eutectic solvents (DESs) and natural deep eutectic solvents (NADES) are synthesized through the combination of hydrogen bond donors and acceptors, such as choline chloride and urea, yielding biodegradable, cost-effective solvents with simpler production processes compared to ionic liquids (ILs) [7, 9]. Perna et al. (2020) underscore the environmentally benign attributes of DESs, highlighting their capacity to replace toxic solvents in extraction and synthesis processes [7]. However, large-scale production reliant on natural compounds, such as plant-derived acids, may exert ecological pressure if not sustainably managed, particularly in regions with limited biomass resources [7]. Relative to ILs, DESs exhibit enhanced sustainability due to their non-toxic precursors and reduced energy requirements for synthesis; nevertheless, their limited thermal stability constrains their applicability in high-temperature processes, as noted by Gallant et al. (2024) [34]. Advances in molecular engineering or hybrid formulations, such as water-DES systems, offer potential solutions to enhance stability and expand their utility across diverse applications [7, 15].

In food processing, DESs demonstrate significant potential for sustainable extraction. Zhang et al. (2025) investigated the use of DESs for extracting oat saponins from Taigu, Shanxi, China, leveraging their low environmental impact, recyclability, and high extraction efficiency [35]. Optimization of parameters, including solid-liquid ratios and salt addition, facilitated superior saponin yields; however, challenges such as solvent degradation under ultrasound-assisted conditions due to pH adjustments with chemicals (e.g., hydrochloric acid, sodium hydroxide) and difficulties in achieving critical temperatures for phase separation persist. Similarly, Qiu et al. (2025) explored DESs for the environmentally benign separation of m-cresol, reporting solvation free energies of 1,4–1,5 kJ/mol for betaine- and alcohol-based DESs, with π-π interactions enhancing solvency compared to ketone and alcohol solvents [36]. Low solubility and high viscosity, however, can impair extraction efficiency and system stability, necessitating optimization of temperature and DES composition [52]. Both studies affirm DESs' alignment with green chemistry principles while emphasizing the need for further research into chemical stability and scalability for industrial applications [35, 36].

In the oil and gas sector, NADES are increasingly recognized for their role in sustainable processes, particularly enhanced oil recovery (EOR). Husain and Abu-Jdayil (2025) evaluated NADES for their biodegradability, non-toxicity, and cost-effectiveness, demonstrating their ability to modify wettability, reduce interfacial tension, and inhibit shale by disrupting hydrogen bonds in clay-rich formations [37]. For example, the formic acid/choline chloride NADES exhibits a melting point of 200°C and an activation energy of 47,72 kJ/mol, with water dilution reducing viscosity and enhancing electrical conductivity. Synergistic interactions with ionic liquids, such as 1-methyl-3-ethylimidazolium chloride (MEIC), further improve solubility and performance in EOR and shale inhibition. Despite their promise, the optimization of NADES formulations for large-scale field applications remains a critical research priority.

The integration of DESs into extraction, synthesis, and industrial processes underscores their potential to balance efficacy, sustainability, and scalability. Nonetheless, challenges related to thermal stability, viscosity, sustainable sourcing of raw materials, and scalability necessitate continued investigation to fully realize their industrial potential.

B. Production of bio-based solvents and their sustainability advantages

Bio-based solvents, derived from renewable biomass sources such as corn, sugarcane, lignocellulosic residues, and palm oil by-products, offer a sustainable alternative to petroleum-derived solvents like hexane, N-methyl-2-pyrrolidone (NMP), and dimethylformamide (DMF) due to their low toxicity, biodegradability, and alignment with green chemistry principles [38, 39]. For instance, 2-methyltetrahydrofuran (2-MeOx), synthesized from lignocellulosic biomass, is approved for food applications in the European Union (EU Commission Directive, 2023) and excels in extracting bioactive compounds, such as polyphenols from grape seeds, owing to its high polarity and favorable solvation properties [40, 41]. Similarly, PolarClean, an ethyl methyl carbonate-based solvent, facilitates the production of high-performance nanofiltration membranes using bio-based polymers like poly (4,5-tricarbonyl-6-glycolic butyrolactone) [P(4,5-T6GBL)], achieving a significantly reduced ecological footprint compared to conventional solvents [42]. These solvents are versatile, finding applications in organic synthesis, polymerization, phytoextraction, high-performance liquid chromatography (HPLC), pharmaceutical purification, solvent recovery, and water treatment via nanofiltration [11, 39, 42]. Ayyildiz et al. (2023) emphasize the valorization of palm oil by-products for producing bioactive solvents, with refining by-products such as gums yielding valuable antioxidants, thereby reducing waste and enhancing product value in alignment with circular economy principles [39]. This approach not only mitigates environmental impact but also promotes resource efficiency by repurposing agricultural and industrial waste streams.

Despite these advantages, bio-based solvents face significant challenges. Large-scale fermentation processes for solvents like ethanol and n-butanol can strain agricultural resources, potentially leading to land use competition and food security concerns, particularly in regions with limited arable land [41]. Energy-intensive extraction processes, especially when reliant on non-renewable energy sources, may diminish sustainability benefits, as noted by Rani and Shanker (2019) [42]. For example, while glycols and esters derived from vegetable oils exhibit excellent organic solubility and low environmental impact, their production often requires energy-intensive methods that could offset ecological gains if not optimized [42]. Makoś et al. (2020) further highlight the limited applicability of bio-based solvents in nanotechnology due to the lack of tailored formulations, underscoring the need for advanced, energy-efficient extraction technologies and region-specific life cycle assessments (LCAs) to evaluate environmental impacts relative to conventional solvents [39]. Integrating biocatalysis with renewable energy sources, such as solar or wind power, could minimize energy inputs and by-products, but high infrastructure costs currently limit scalability and widespread adoption, particularly in cost-sensitive industries [40]. For instance, ethanol production from sugarcane is well-established, yet regional variations in energy demands necessitate localized LCAs to ensure sustainability claims are robust [41].

In environmental remediation, bio-based solvents and biosorption techniques provide innovative solutions for wastewater treatment and industrial effluent management. Green-synthesized nanomaterials, produced using solvents like ethanol, demonstrate high adsorption capacities for organic dyes, contributing to Sustainable Development Goal 6 (Clean Water and Sanitation) by mitigating water pollution in textile and chemical industries [43]. Biosorption, utilizing renewable biomass such as algal or fungal materials, enables low-energy extraction of toxic metals (e.g., lead, cadmium, mercury) from effluents. Pamukoglu and Kargi (2006) report that powdered waste sludge (PWS) from municipal wastewater treatment plants achieves a maximum copper (II) ion adsorption capacity of 150 mg Cu^{2+}/g at pH 5, with smaller particle sizes (e.g., 53 μm) enhancing efficiency due to increased surface area [44]. Hybrid systems combining biosorption with bio-based solvents or deep eutectic solvents (DESs) offer synergistic benefits by leveraging DES solubility and biosorbent renewability for heavy metal removal, thereby reducing reliance on hazardous chemicals and minimizing waste generation [7, 44]. However, challenges such as energy-intensive solvent synthesis, high nanomaterial production costs, and scalability barriers persist, necessitating further research into cost-effective production methods and infrastructure development [45]. Comprehensive LCAs are critical to quantify the full environmental impact of these processes, ensuring that sustainability claims are substantiated across the solvent lifecycle.

The integration of bio-based solvents into industrial and environmental applications underscores their potential to balance efficacy and sustainability. By addressing challenges through innovations in energy-efficient extraction, sustainable feedstock sourcing, and hybrid system development, bio-based solvents can advance green chemistry objectives and support sustainable manufacturing. Future research should prioritize standardized sustainability metrics, interdisciplinary applications, and policy frameworks to enhance scalability and industrial adoption, positioning bio-based solvents as a cornerstone of environmentally responsible chemical processes.

C. Characteristics and sustainability challenges of ionic liquids

Ionic liquids (ILs) are distinguished by their negligible volatility and exceptional thermal stability, rendering them highly effective for high-temperature applications, including catalysis, electrochemical processes, and pharmaceutical synthesis [10]. Earle and Seddon (2000) emphasize the remarkable versatility of ILs, highlighting their ability to dissolve a diverse array of compounds, thereby enabling efficient extraction and synthesis processes [16]. However, their synthesis often involves toxic precursors, such as halogenated compounds, which compromises their alignment with green chemistry principles, as elucidated by Welton (2018) [45]. To mitigate this, Welton advocates for the development of biodegradable ILs derived from renewable feedstocks, such as amino acids, though their complex synthetic pathways render them less sustainable than deep eutectic solvents (DESs) or bio-based solvents [43]. While ILs demonstrate superior performance in pharmaceutical applications, their environmental footprint during production underscores the need for innovations in renewable precursor development and streamlined synthesis processes to enhance sustainability [10, 43].

Widyaningsih et al. (2025) explored the application of betaine-cis-oleic acid-based eutectic ionic liquids (EILs) for the recovery of rare earth elements (REEs) from red mud, a byproduct of aluminum production [46]. The optimized EIL composition, with a 1:4 betaine:cis-oleic acid ratio, exhibited low toxicity, biodegradability, and recyclability, achieving extraction efficiencies of 50,86% for scandium (Sc), 55,68% for cerium (Ce), 53,93% for europium (Eu), 81,65% for erbium (Er), and 86,62% for yttrium (Y) [46]. Analytical techniques, including X-ray diffraction (XRD) and scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX), confirmed the formation of an orthorhombic phase in the post-extraction crystal structure of red mud, while nuclear magnetic resonance (NMR) and X-ray fluorescence (XRF) analyses validated the structural integrity of EILs after three reuse cycles [55]. Techno-economic analysis demonstrated industrial viability, with a 2,1-year payback period and a positive net present value (NPV); however, challenges such as low solubility and high viscosity pose barriers to scalability [55]. This approach provides a sustainable alternative to conventional acid leaching, aligning with circular economy principles by valorizing industrial byproducts [46, 47]. Compared to DESs and bio-based solvents, EILs offer enhanced selectivity for REEs but face analogous limitations in production scalability and environmental impact [7, 43].

The integration of ILs into high-value applications underscores their potential to advance sustainable industrial processes. Nevertheless, challenges related to precursor toxicity, energy-intensive synthesis, and scalability necessitate ongoing research into biodegradable ILs, renewable feedstocks, and optimized production methodologies to fully align with green chemistry objectives.

V.TOWARDS GREENER PROCESSES: RENEWABLE SOLVENTS FOR INDUSTRY

Green chemistry principles advocate minimizing energy consumption, waste generation, and toxicity in solvent production to advance environmental sustainability. Supercritical fluids, such as supercritical carbon dioxide (CO_2) and ethanol, are recognized for their recyclability and non-toxic properties, making them sustainable alternatives for extraction processes. Piqueras et al. (2015) emphasize that supercritical ethanol, with its lower critical temperature compared to CO_2, reduces energy requirements in extraction applications, thereby enhancing sustainability [48]. However, the high-pressure infrastructure required for supercritical fluid production increases operational costs and limits scalability [5]. Integrating renewable energy sources, such as solar or wind power, and advanced waste recycling systems can mitigate environmental impacts, yet significant infrastructure costs hinder widespread adoption. For instance, closed-loop systems for supercritical CO_2 recycling are effective but demand substantial capital investment, restricting their applicability in small-scale industries. In contrast, deep eutectic solvents (DESs) and bio-based solvents offer simpler, less toxic production pathways, aligning closely with green chemistry principles, though sustainable scaling remains a challenge.

The environmental and toxicological risks associated with conventional organic solvents have driven demand for renewable solvent alternatives in industrial applications [49]. Green solvents, including vegetable oils, supercritical CO_2, DESs, and limonene, provide significant advantages over traditional methods for extracting carotenoids from fruit and vegetable by-products [50]. A key benefit of these solvents is their suitability for direct incorporation of extracted compounds into food products. For example, Ordóñez-Santos et al. (2021) demonstrated that carotenoids extracted from mandarin peels using sunflower oil were effectively utilized as natural colorants in bread and cakes [51]. Similarly, Sanchez-Camargo et al. (2019) reported that β-carotene extracted from mango peels via supercritical CO_2 significantly enhanced the oxidative stability of sunflower oil. However, industrial-scale implementation faces challenges, including high initial capital costs and, in some cases, lower extraction yields [52]. Recent studies suggest that hybrid approaches, such as ultrasound-assisted green extraction, may address these limitations [53].

In the food and cosmetics industries, the adoption of renewable solvents not only promotes environmental sustainability but also meets growing consumer demand for natural ingredients [54]. De Souza Mesquita et al. (2020) confirmed that carotenoids extracted from palm fruit waste using ionic liquids can be successfully applied in antimicrobial packaging materials [55]. Deep eutectic solvents (DESs), composed of hydrogen bond acceptors (HBAs) and hydrogen bond donors (HBDs) with low melting points, offer advantages over traditional ionic liquids, including lower cost, biodegradability, and reduced toxicity. Notably, natural deep eutectic solvents (NADESs), derived entirely from natural components such as plant metabolites, have found extensive applications in the pharmaceutical and food industries [56]. For instance, NADESs composed of choline chloride and glycerol have been successfully employed in the extraction of bioactive compounds and catalytic processes.

Biomass-derived solvents are recognized as viable alternatives due to their sustainable sourcing and carbon-neutral properties. Solvents such as ethanol, isopropanol, and ethyl lactate are widely utilized in analytical methods, such as reversed-phase liquid chromatography (RP LC), owing to their high biocompatibility and low environmental footprint [57]. Additionally, carbonate-based solvents, such as dimethyl carbonate (DMC) and propylene carbonate, are increasingly adopted in industrial applications due to their high polarity and low toxicity. Water, considered the most sustainable solvent, faces limitations in dissolving non-polar compounds, necessitating modifications in certain applications. Techniques such as subcritical water chromatography (SBWC) and micellar liquid chromatography (MLC) leverage the altered physicochemical properties of water under elevated temperature and pressure or through surfactants to significantly reduce organic solvent consumption.

Green synthesis methods, such as electrocatalysis and photocatalysis, show promise in converting biomass-derived platform chemicals into high-value products. For example, the photocatalytic oxidation of glucose to produce gluconic acid and the electrocatalytic oxidation of 5-hydroxymethylfurfural (HMF) to synthesize 2,5-furandicarboxylic acid (FDCA) demonstrate the industrial potential of these approaches [57]. Integration with renewable energy sources further reduces the carbon footprint of these processes. Levent et al. (2016) investigated the extraction of boric acid from tincal mineral using supercritical ethanol, offering an environmentally benign alternative to conventional sulfuric acid-based methods. Operating at 250°C and 7,4 MPa, this method facilitates the esterification of boric acid into volatile triethyl borate, achieving a maximum extraction efficiency of 32,6 wt% [59]. By minimizing the use of hazardous chemicals and eliminating impurity dissolution steps, this approach aligns with green chemistry principles, promoting energy efficiency and reduced environmental impact. Pamukoglu et al. (2022) demonstrated the green synthesis of silica-amine functionalized iron nanoparticle (SiNH2@FeNP) nanocomposites using liquorice root extract [60]. Biomolecules such as flavonoids and polyphenols serve as reducing and stabilizing agents, eliminating the need for toxic chemical reductants. With a surface area of 236,1 m^2/g and adsorption parameters optimized via Box-Behnken design, the nanocomposite exhibits superior methylene blue removal from wastewater, exemplifying sustainable material synthesis through renewable plant-based resources [60]. This approach aligns with green chemistry's emphasis on safer and sustainable production methodologies.

Biodiesel, a renewable nonpolar solvent derived from vegetable oils and animal fats, serves as an effective alternative to toxic solvents like chloroform and ethyl acetate in dispersive liquid-liquid microextraction (DLLME) [27, 61]. Achieving extraction efficiencies of 90–100% for nonpolar species and recoveries of 99–100% for Cu(II), biodiesel demonstrates high performance in extracting analytes such as crystal violet and methyl orange. Requiring minimal solvent (200 µL biodiesel, 200 µL ethanol) and generating low waste (0,6 mL per determination), biodiesel's high boiling point (>200°C), pH stability, and purity make it suitable for diverse analytical applications. Evaluated using Green Star (92/100) and AGREE (0,81) metrics, biodiesel's renewable sourcing and minimal environmental impact underscore its alignment with green chemistry principles, offering a safer, cost-effective, and sustainable option.

The widespread use of conventional organic solvents poses significant environmental and health risks due to their toxic, volatile, and petroleum-derived nature. Consequently, innovative solvents, such as bio-based solvents, ionic liquids, DESs, and supercritical fluids, are gaining attention for their potential in industrial applications [62]. Bio-based solvents, derived from lignocellulosic biomass and glycerol, are distinguished by their low toxicity and biodegradability [63]. For instance, Cyrene™, with its polar aprotic properties, serves as a viable substitute for traditional solvents like N-methyl-2-pyrrolidone (NMP) or dimethylformamide (DMF) in polymeric membrane production. Similarly, solvents such as dimethyl isosorbide (DMI) and γ-valerolactone (GVL) are preferred due to their high solubility capacities and minimal environmental impact [64]. Ionic liquids, characterized by low vapor pressure and tunable physicochemical properties, offer an effective alternative for dissolving cellulose and other biopolymers, though their high costs and complex synthesis processes limit widespread adoption [65]. In contrast, DESs provide a more cost-effective and less toxic option, with both hydrophilic and hydrophobic DESs showing promise in membrane technology applications [66, 67]. Supercritical CO_2, a prominent green solvent, is valued for its non-toxicity and low cost, with its high diffusion coefficient and low surface tension optimizing phase separation processes in polymeric membrane production [25, 50, 68]. However, the requirement for high-pressure conditions and specialized equipment hinders its industrial application.

The integration of green solvents into industrial processes is a pivotal step toward achieving sustainable production goals. Evaluating these solvents in terms of performance, cost, and scalability, as detailed in Table 5 [69, 70], remains a critical focus for future research [69]. Furthermore, comprehensive assessment of their environmental impact through methods such as life cycle analysis (LCA) will significantly contribute to sustainability objectives [70]. Collaboration between academia and industry plays a crucial role in the development and implementation of innovative solvent technologies [32, 71]. The adoption of green solvents not only reduces environmental footprints but also enhances economic efficiency, paving the way for a more sustainable industrial future.

Table 5. Production and performance characteristics of green solvents

Green Solvent	Chemical Formula	Production Method	Description	Advantages	Challenges	Ref.
DES	-	Mixture and Physical Combination	DES is produced by mixing organic and inorganic salts with solvents.	Easy and low-cost production, environmentally friendly	Structure control can be difficult, lack of standardization	[72]
Ionic Liquids	-	Electrochemical Synthesis, Reactions	Transformation of chemical compounds into ionic liquids by electrolysis.	Low vapor pressure, versatile solvents	High cost, production difficulties	[73]
Supercritical Carbon Dioxide	CO_2	Supercritical State Technology	Carbon dioxide is brought to supercritical state at high pressure and temperature.	Environmentally friendly, biodegradable	High energy requirements	[74]
Limonene	$C_{10}H_{16}O$	Extraction from Natural Sources	Obtained by steam distillation from citrus fruits.	Natural, biodegradable	Limited resources, activity variability	[75]
Ethyl Lactate	$C_6H_{12}O_3$	Fermentation and Biotechnological Methods	Produced biotechnologically by sugar alcohol fermentation.	Natural, environmentally friendly	Production efficiency may decrease	[76]
Propylene Carbonate (PC)	$C_4H_6O_3$	Chemical Synthesis, Process Control	Obtained by reaction of propylene oxide and carbon dioxide.	High biocompatibility, non-toxic	Substances used in chemical synthesis are expensive	[77]

N-Methyl-2-Pyrrolidone (NMP)	C_5H_9NO	Chemical Synthesis, Solvent Reactions	Produced by methylation of pyrrolidone derivatives.	High solubility, biodegradable	High cost, production difficulties	[78]
Tetrahydrofuran (THF)	C_4H_8O	Chemical Synthesis, Straight Reactions	Tetrahydrofuran is obtained by hydrogenation of butadiene.	High solubility, low toxicity	Energy requirements during production	[79]
Dimethyl Ether (DME)	C_2H_6O	Natural Gas and Chemical Reactions	Dimethyl ether is produced by dehydrogenation of methanol.	Low environmental impact, biocompatibility	High production costs, limited resources	[80]
Glycerol	$C_3H_8O_3$	Biotechnological Method, Fatty Acid Fermentation	It is produced biotechnologically with fatty acid methyl esters.	Safe, biodegradable	Production efficiency can be time consuming	[81]
Benzyl Alcohol	$C_6H_5CH_2OH$	Chemical Synthesis, Acidic Reactions	It is obtained by oxidation of benzene derivatives.	High solubility, biocompatibility	High toxicity risks, costly production	[82]
Ethyl Acetate	$C_4H_8O_2$	Esterification Reaction	It is produced by reaction between acetic acid and ethanol.	High solubility, biodegradable	Potentially toxic by-products	[83]
Supercritical Methanol	CH_3OH	Reactions in Supercritical Phase	Methanol is made supercritical and subjected to various chemical reactions.	Low environmental impact, high efficiency	High energy consumption, production costs	[84]
Furfurol	$C_5H_4O_2$	Fermentation, Chemical Processes	Furfurol is obtained by converting sugar into furan derivatives with fermentation.	Biodegradable, environmentally friendly	Biotechnological methods are difficult, low efficiency	[85]
Supercritical Ammonia	NH_3	Supercritical Phase Technology	Ammonia is processed by providing solubility in supercritical state.	High solubility, low environmental impact	High temperature and pressure requirements	[86]

VI.CONCLUSION

A bibliometric analysis of 21.991 articles from ScienceDirect (2010–2025) reveals a marked increase in green solvent research since 2020, with 2024 representing the peak year, propelled by global sustainability imperatives, including volatile organic compound regulations and sustainable development goals. However, the predominance of chemistry and chemical engineering disciplines, alongside a reliance on quantitative methodologies, restricts interdisciplinary perspectives and applications in areas such as biotechnology, nanotechnology, and wastewater treatment. Keyword analysis identifies catalysis as a primary research focus but highlights a deficiency in sustainability metrics, such as lifecycle emissions and circular economy integration, underscoring the critical need for comprehensive life cycle assessments (LCAs).

Established frameworks for evaluating green solvents offer robust methodologies for assessing environmental impact and performance. Research on deep eutectic solvents (DESs) emphasizes their cost-effectiveness and biodegradability compared to ionic liquids (ILs), while studies advocating biodegradable IL alternatives align with green chemistry principles. These efforts signal a transition toward application-oriented research, yet the absence of standardized sustainability metrics poses a persistent challenge. Combining evaluation frameworks with practical insights could facilitate the development of unified assessment tools, incorporating LCAs for applications such as heavy metal and dye removal.

Comparative analysis indicates that DESs excel in cost and biodegradability but are limited by thermal instability, rendering them suitable for biocatalysis but less effective for high-temperature processes. Supercritical CO_2 and ethanol perform strongly in extraction but face scalability constraints due to high infrastructure costs. Bio-based solvents, such as ethanol and limonene, are renewable yet resource-intensive, necessitating optimized production methods. Emerging applications in wastewater treatment, including biosorption for heavy metal removal and nanomaterial-based dye removal, align with clean water and sanitation objectives but are impeded by scalability and cost challenges. Hybrid systems, such as water-DES combinations or biosorption-solvent extraction, present promising solutions but remain underexplored. The surge in publications reflects policy-driven momentum, yet a focus on incremental progress over transformative innovation, coupled with disciplinary concentration and limited sustainability metrics, hampers advancement.

To advance green solvent research, future efforts should prioritize:

Comprehensive LCAs: Quantify environmental impacts across the solvent lifecycle to substantiate sustainability claims, particularly for wastewater treatment applications.

Interdisciplinary Applications: Expand the use of low-toxicity solvents in biotechnology, nanotechnology, and environmental remediation, including bioprocessing and heavy metal removal.

Hybrid Solvent Systems: Develop synergistic combinations, such as water-DES or biosorption-solvent systems, to optimize performance and sustainability.

Policy and Economic Frameworks: Establish incentives and infrastructure to facilitate industrial adoption, aligning with global sustainability policies.

Sustainable Production Innovations: Integrate renewable energy, waste recycling, and sustainable feedstocks to enhance production efficiency, as demonstrated by supercritical ethanol and bio-based nanomaterials.

While limited by its reliance on a single database, potentially excluding literature from other sources, this analysis provides a solid foundation for advancing green solvent research. By addressing scalability, interdisciplinary applications, and standardized sustainability metrics, green solvents can emerge as a cornerstone of sustainable chemistry, transforming chemical processes across industries in alignment with global environmental objectives.

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