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Advancing Sustainable Chemical Processes through the Use of Green Solvents and Reaction Media

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Abstract

The push for sustainable chemical processes underscores the importance of green solvents and reaction media as eco-friendly alternatives to conventional, often harmful chemicals. Traditional solvents, widely used in industrial processes, pose risks to health, deplete resources, and cause pollution. Green solvents, derived from renewable sources and characterised by their low toxicity, biodegradability, and minimal environmental impact, offer a viable solution. This review examines green solvents' classifications, properties, and applications in solvent extraction, organic synthesis, polymerisation, and industrial cleaning. Key types, including bio-based solvents, supercritical CO_2, ionic liquids, deep eutectic solvents, and fluorinated solvents, present unique sustainability advantages. Green reaction media also enhance reaction efficiency, selectivity, and safety while reducing waste and energy use. Despite scalability and cost challenges, advancing green chemistry principles through interdisciplinary collaboration and research could drive the chemical industry towards sustainability and global environmental progress.

Keywords: *Bio-Based Solvents; Environmental Impact; Green Solvents; Reaction Media; Renewable Resources; Sustainable Chemistry*

Introduction

In modern chemical processes, the choice of solvents and reaction media plays a fundamental role in determining the efficiency and outcome of reactions (Sun *et al*., 2024). However, the impact of these solvents extends far beyond the lab or industrial setting, as the widespread use of conventional solvents presents serious environmental and health concerns (Martínez-Pérez-Cejuela & Gionfriddo, 2024). Traditional solvents, such as chlorinated hydrocarbons, aromatic hydrocarbons, and volatile organic compounds (VOCs), are widely used for their ability to dissolve reactants and facilitate a range of chemical transformations (Huang *et al*., 2024). These solvents, though effective, are often toxic, non-biodegradable, and derived from non-renewable sources, contributing to air, water, and soil pollution. They pose a multitude of risks, including occupational hazards, ecological damage, and contributions to climate change due to their persistence and volatility (Li *et al*., 2024a).

The production, use, and disposal of conventional solvents result in significant emissions of hazardous air pollutants (HAPs), greenhouse gases (GHGs), and other toxic substances, exacerbating the environmental footprint of the chemical industry. The impact on human health is equally concerning (Khan *et al*., 2023). Many traditional solvents are known carcinogens or neurotoxins, causing both acute and chronic health issues. Workers exposed to these chemicals in industrial or laboratory settings often experience skin irritation, respiratory distress, neurological effects, and, in severe cases, long-term illnesses such as cancer or liver damage (Otitolaiye, Al-Naaimi & Abdelrahim, 2024). The volatility of these compounds leads to their release into the atmosphere, contributing to poor air quality and increasing the risk of occupational exposure. In addition to the direct risks to workers, solvent emissions contribute to broader public health challenges, including respiratory diseases linked to air pollution (Zhou *et al*., 2023). Furthermore, the environmental persistence of conventional solvents means that they often bioaccumulate, disrupting ecosystems and posing long-term ecological risks, including contamination of water sources and soil (Iyiola *et al.*, 2024). In light of these pervasive issues, it has become increasingly clear that the continued reliance on traditional solvents is unsustainable, both for human health and the environment. The need for safer, more environmentally benign alternatives is more urgent than ever.

This is where the principles of sustainable chemistry, specifically green chemistry, come into focus. Green chemistry emphasises the design of chemical products and processes that reduce or eliminate the generation of hazardous substances. These principles align with the growing recognition that the chemical industry must shift towards more sustainable practices to mitigate its environmental impact and safeguard human health. One of the foundational principles of green chemistry is the development and use of safer solvents and reaction media (Shaoo & Banik, 2024). Green chemistry encourages the replacement of toxic, non-renewable solvents with alternatives that are non-toxic, renewable, and biodegradable, thereby reducing the overall ecological footprint of chemical processes (Naeem *et al*., 2024). By minimizing the production of hazardous waste and utilising renewable resources, green chemistry aims to create processes that are not only effective but also sustainable in the long term (Mohan *et al*., 2024). This approach not only aligns with global environmental goals but also addresses growing regulatory pressures and societal demands for safer chemical practices. The adoption of green solvents and reaction media is crucial for advancing the goals of green chemistry (Sharma, Gallou & Handa, 2024). Green solvents are typically defined by their reduced toxicity, biodegradability, and minimal environmental impact. Many are derived from renewable resources, such as plants or biomass, and can be recycled or safely disposed of without causing harm to the environment (de Souza Mesquita *et al*., 2024). These solvents present an opportunity to minimise the environmental and health risks associated with traditional solvents while maintaining the efficiency and functionality required for industrial and research applications. For example, water, supercritical carbon dioxide, ionic liquids, deep eutectic solvents, and bio-based solvents are among the most prominent alternatives being explored and implemented in various fields of chemistry (Dongare *et al*., 2024). These solvents not only meet the criteria for environmental sustainability but also offer unique properties that can enhance the efficiency of chemical reactions, such as improved selectivity, lower energy requirements, and reduced waste generation (González-Campos *et al*., 2024). The incorporation of such solvents into mainstream chemical processes can significantly reduce the industry's dependence on harmful substances and help transition toward a more circular economy, where resources are reused and recycled.

The purpose of this review paper is to provide an in-depth analysis of green solvents and reaction media, emphasizing their potential to transform the chemical industry into a more sustainable enterprise. This review will explore the classification, properties, and applications of green solvents, illustrating how they can replace conventional solvents in a wide range of chemical processes, from solvent extraction and organic synthesis to polymerisation and industrial cleaning. By offering a comprehensive overview of the current landscape of green solvents, this paper aims to highlight both the progress that has been made and the challenges that remain in achieving widespread adoption of these environmentally friendly alternatives. Special attention will be given to the practical applications of green solvents in industrial and laboratory settings, as well as the economic and scalability considerations that influence their implementation. Furthermore, this review will address the future directions for research and innovation in this field, advocating for continued investment in the development of novel solvents and reaction media that are not only greener but also more efficient and cost-effective. By fostering collaboration between academia, industry, and regulatory bodies, the chemical industry can take significant steps toward realising a more sustainable future, wherein the principles of green chemistry become the norm rather than the exception. Green solvents and reaction media hold immense potential to reduce the ecological footprint of chemical processes while also improving safety and efficiency. This review aims to contribute to the ongoing discourse on sustainable chemistry by offering a thorough examination of the available green solvents (Figure 1) and their practical applications, as well as by identifying the barriers to their widespread adoption. The transition to green solvents is not without its challenges, but with continued research, innovation, and a commitment to sustainability, the chemical industry can pave the way for a greener, safer, and more responsible future.

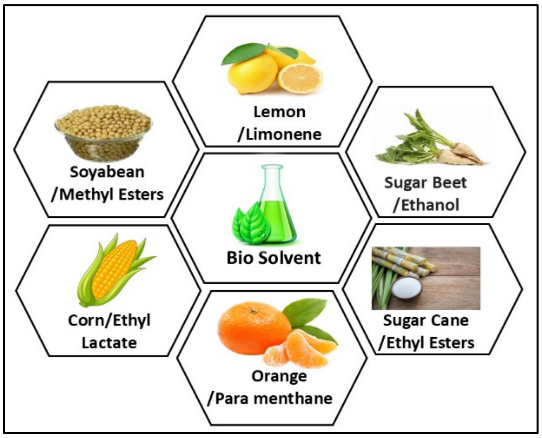

Figure 1: Schematic Representation of Different Sources of Green Solvents *(Source: Author)*

Traditional Solvents and Their Environmental Impact

In the realm of chemical processes, conventional solvents such as chlorinated hydrocarbons, aromatic hydrocarbons, and volatile organic compounds (VOCs) have long served as critical agents for dissolving reactants and facilitating various reactions (Ruan *et al.*, 2023). These solvents are prized for their solvating power, versatility, and capacity to dissolve a wide range of organic and inorganic compounds, making them indispensable in both laboratory research and large-scale industrial operations. Chlorinated hydrocarbons, such as chloroform, dichloromethane, and carbon tetrachloride, are often used in processes like extraction, degreasing, and dry cleaning due to their strong solvating capabilities (Mohr & Hatton, 2020). Aromatic hydrocarbons, such as benzene, toluene, and xylene, find extensive applications in the manufacture of plastics, pharmaceuticals, and paints (Saggu & Kumar, 2025), while volatile organic compounds (VOCs), which include a broad class of organic chemicals like acetone, hexane, and ethyl acetate, are frequently employed as solvents in adhesives, coatings, and cleaning products (Mangotra & Singh, 2024). Despite their widespread use and effectiveness, these traditional solvents present substantial risks due to their environmental persistence, toxicity, and tendency to volatilise into the atmosphere.

Chlorinated hydrocarbons, for example, are notorious for their environmental impact. These compounds are highly persistent in the environment, often bioaccumulating in ecosystems and causing long-term harm to wildlife. Their widespread use has led to significant contamination of air, water, and soil (Said & El Zokm, 2024). For instance, dichloromethane and chloroform are known to degrade slowly in the atmosphere, contributing to ozone depletion and global warming (Roozitalab *et al*., 2024). When released into the environment, they can accumulate in water bodies, posing risks to aquatic life due to their toxicity and ability to disrupt biological processes. Similarly, aromatic hydrocarbons like benzene are highly toxic and carcinogenic, with prolonged exposure linked to severe health issues such as leukaemia (Saeedi, Malekmohammadi & Tajalli, 2024). Benzene is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), and its presence in industrial effluents poses a significant public health risk (Zahed *et al*., 2024). Benzene and other aromatic hydrocarbons are also volatile, readily vaporising into the atmosphere and contributing to the formation of ground-level ozone and smog, both of which are major components of air pollution (Isha *et al*., 2024). VOCs are perhaps the most pervasive class of traditional solvents in terms of environmental impact. These compounds are highly volatile, and their emissions contribute to poor indoor and outdoor air quality. VOCs are responsible for the formation of photochemical smog, which not only degrades air quality but also exacerbates respiratory conditions such as asthma and bronchitis in humans (Edo *et al*., 2024).

The health risks associated with traditional solvents are well-documented, affecting both workers in industrial settings and the general population through environmental exposure. Many of these solvents are classified as carcinogens, mutagens, or teratogens, meaning they can cause cancer, genetic mutations, or birth defects, respectively (Vulimiri *et al*., 2022). Chlorinated hydrocarbons, for example, are known to cause liver and kidney damage with prolonged exposure, and carbon tetrachloride is a potent hepatotoxin, causing liver failure in individuals exposed to high levels. Moreover, these solvents are highly volatile, meaning that even short-term exposure can lead to acute health effects such as dizziness, headaches, nausea, and respiratory irritation (Hahn, Botzenhart & Schweinsberg, 2024). Long-term exposure, particularly in occupational settings, can result in chronic conditions, including neurological damage, immune system suppression, and reproductive toxicity. Aromatic hydrocarbons like toluene and xylene have also been implicated in a range of health issues, from central nervous system depression to organ damage. Toluene exposure, even at relatively low levels, has been linked to cognitive impairments, while xylene can cause serious effects on the liver and kidneys (Rajput, Singh & Bhardwaj, 2025). Volatile organic compounds, due to their tendency to vaporise at room temperature, pose significant inhalation hazards. Workers in industries where VOCs are commonly used, such as painting, coating, and cleaning, are at particularly high risk of exposure. Short-term inhalation of VOCs can cause eye, nose, and throat irritation, headaches, and fatigue, while long-term exposure can result in more severe effects, such as liver and kidney damage or central nervous system disorders. Additionally, VOCs contribute to poor indoor air quality, a growing concern in both residential and industrial environments. For example, formaldehyde, a common VOC used in manufacturing, has been classified as a human carcinogen, and its presence in building materials, furnishings, and household products can lead to continuous low-level exposure, particularly in poorly ventilated spaces (Bhat *et al*., 2024). Moreover, when released into the environment, VOCs react with nitrogen oxides in the presence of sunlight to form ozone and secondary organic aerosols, which are key components of smog. Smog is not only a significant environmental pollutant but also a major health hazard, as it has been linked to respiratory problems, cardiovascular diseases, and premature mortality (Yuan *et al.,* 2024).

Beyond the direct health risks, the environmental implications of traditional solvent use are profound, contributing to pollution, toxicity, and resource depletion. Chlorinated hydrocarbons, for example, persist in the environment, undergoing minimal biodegradation, which allows them to accumulate in ecosystems over time. This persistence leads to contamination of air, water, and soil, posing long-term risks to both human and ecological health. In aquatic environments, these solvents can be particularly harmful, as they tend to bioaccumulate in the tissues of aquatic organisms, leading to biomagnification in food chains and adverse effects on biodiversity (Adeola *et al*., 2024). For instance, chlorinated solvents like trichloroethylene (TCE) are frequently detected in groundwater contamination sites, creating significant challenges for water treatment facilities and posing risks to communities reliant on these water sources. Moreover, the reliance on conventional solvents contributes to resource depletion, as many of these chemicals are derived from non-renewable fossil fuels (Gürses *et al*., 2024). The extraction and processing of petroleum to produce solvents not only consumes finite natural resources but also results in significant carbon emissions, contributing to climate change. For example, the production of aromatic hydrocarbons such as benzene and toluene involves energy-intensive refining processes that release large quantities of CO_2 and other greenhouse gases into the atmosphere (Modirzadeh *et al*., 2024). Furthermore, the disposal of traditional solvents often presents additional environmental challenges. Improper disposal methods, such as incineration or landfilling, can result in the release of harmful by-products, including dioxins and furans, which are highly toxic and can persist in the environment for decades.

Green Chemistry: Principles and Guidelines

Green chemistry, also known as sustainable chemistry, represents a paradigm shift in chemical science and engineering. Its aim is to design chemical products and processes that reduce or eliminate the generation of hazardous substances (Verma *et al*., 2024). Developed in response to the growing environmental concerns linked to conventional chemical practices, green chemistry seeks to create a more sustainable future by focusing on pollution prevention at the molecular level rather than relying on end-of-pipe treatment solutions. The 12 core principles of green chemistry, first articulated by Paul Anastas and John Warner in 1998, serve as a framework for guiding chemists toward more environmentally benign practices (Cannon *et al*., 2024). These principles emphasise the importance of preventing waste, designing safer chemicals, using renewable feedstocks, and improving energy efficiency, among others. Within this context, solvent choice plays a critical role. Traditional solvents, as previously discussed, are among the most significant contributors to chemical waste and pollution. Consequently, the selection of greener solvents aligns with several key principles of green chemistry, particularly those aimed at reducing toxicity, enhancing safety, and improving the sustainability of chemical processes.

One of the central tenets of green chemistry is the careful selection and design of solvents that minimise environmental harm while maintaining efficacy in facilitating chemical reactions (Banjare *et al*., 2024). Solvents are involved in nearly all stages of chemical production, from synthesis and purification to product formulation and application. Therefore, the choice of solvent directly impacts the overall sustainability of a process. For a solvent to be considered "green", it must meet several important criteria. First, it should exhibit low toxicity to both humans and the environment. This aligns with the principle of designing safer chemicals, which aims to minimise the adverse health effects associated with chemical exposure (Prabhune & Dey, 2023). Second, green solvents should be biodegradable or readily broken down by natural processes, thus preventing long-term persistence in the environment. Biodegradability ensures that solvents do not accumulate in ecosystems, reducing the risks of bioaccumulation and biomagnification in food chains (Qadeer *et al*., 2024). Additionally, green solvents should be derived from renewable resources rather than non-renewable petrochemical feedstocks. This reflects the principle of using renewable materials, which is critical for reducing the dependence on fossil fuels and mitigating the environmental impacts of resource extraction and processing (Mohammad *et al*., 2023).

Assessing the greenness of solvents requires the use of key metrics that help to quantify their environmental and health impacts. One of the most important metrics is toxicity, which refers to the potential of a solvent to cause harm to humans, animals, and ecosystems (Imam & Abdelrahman, 2023). Solvents with low toxicity profiles are preferred because they pose fewer risks to workers, consumers, and the environment. Another key metric is biodegradability, which measures the ability of a solvent to be broken down by microorganisms into harmless byproducts such as water and carbon dioxide. Solvents that are biodegradable are less likely to persist in the environment and cause long-term contamination. In addition to toxicity and biodegradability, the environmental impact of a solvent is assessed through its potential to contribute to issues like global warming, ozone depletion, and smog formation (Usman *et al.*, 2023). For example, solvents that have high global warming potential (GWP) or contribute to the formation of tropospheric ozone are considered environmentally harmful and should be avoided (Ravanchi & Soleimani, 2023). The volatility of a solvent, measured by its vapour pressure, is another important factor to consider. Volatile solvents can easily evaporate into the atmosphere, contributing to air pollution and posing hazards for inhalation. As such, green solvents should ideally have low volatility to minimise these risks. Finally, energy efficiency is another metric to consider when evaluating solvents. Solvents that require lower energy inputs for synthesis, separation, and recycling are more sustainable, as they help to reduce the overall carbon footprint of chemical processes. This aligns with the green chemistry principle of increasing energy efficiency, which emphasises the importance of minimising energy consumption throughout the lifecycle of a chemical product.

In practice, green solvents encompass a variety of alternative solvent classes, including water, bio-based solvents, supercritical fluids, and ionic liquids (Dutta, 2024). Water, often referred to as the universal solvent, is a particularly attractive option in green chemistry due to its abundance, non-toxicity, and ability to dissolve a wide range of substances. Water-based reactions are already employed in industries such as pharmaceuticals and food processing, and advances in aqueous chemistry continue to expand its applications. However, the limitations of water—such as its high polarity and inability to dissolve certain organic compounds—necessitate the exploration of other green solvent alternatives (Ramos-Villaseñor, Sartillo-Piscil & Frontana-Uribe, 2024). Bio-based solvents, derived from renewable biological sources such as corn, soybeans, and citrus fruits, offer another promising category of green solvents. These solvents, which include bioethanol, limonene, and glycerol, are generally non-toxic, biodegradable, and renewable (Singh *et al*., 2024). Supercritical fluids, such as supercritical carbon dioxide ($scCO_2$), are another green solvent option that has gained popularity due to their unique properties. $scCO_2$, in particular, is valued for its low toxicity, non-flammability, and ability to act as a solvent for a wide range of organic and inorganic compounds. Additionally, $scCO_2$ can be easily removed from reaction products, reducing the need for energy-intensive separation processes (Kessler *et al*., 2024). Ionic liquids, which are salts in liquid form, are another class of green solvents known for their low volatility and tunable properties. While ionic liquids offer many advantages in terms of reduced environmental impact, their biodegradability and toxicity profiles remain areas of active research and development (Lei *et al*., 2024). Each of these solvent classes offers distinct advantages and disadvantages, and their selection should be based on a holistic assessment of the specific needs of a given chemical process.

Classification and Properties of Green Solvents

Green solvents have become critical in modern chemical processes, providing environmentally friendly alternatives to traditional solvents, which often carry significant health and environmental risks. These solvents can be classified into several categories based on their origin, chemical composition, and applications, each offering unique properties that cater to the growing demands of sustainable chemistry (Sharma, Gallou & Handa, 2024). This section provides an in-depth look at the most prominent classes of green solvents: bio-based solvents, water, supercritical CO_2, ionic liquids, deep eutectic solvents (DES), and fluorinated solvents. Each class of solvent possesses distinct characteristics and advantages that contribute to the overall greenness of chemical processes.

Bio-Based Solvents, Water, and Supercritical CO_2 Bio-based solvents are derived from renewable biological sources, such as plants, algae, or microorganisms, and are considered some of the most promising alternatives to traditional petrochemical solvents (Sheldon, 2024). Common examples of bio-based solvents include bioethanol (from the fermentation of corn or sugarcane), glycerol (a byproduct of biodiesel production), and limonene (extracted from citrus fruit peels). These solvents are typically non-toxic, biodegradable, and have a lower environmental footprint compared to their petroleum-derived counterparts (Vasileiadou, 2024). Their synthesis involves simple, energy-efficient processes, often relying on natural resources or waste materials, making them both sustainable and cost-effective. For example, limonene, widely used as a solvent in cleaning products, paints, and coatings, offers the dual benefit of being biodegradable and non-toxic while providing excellent solvency for a variety of applications (Mori, 2023). The environmental benefits of bio-based solvents are clear: by using renewable feedstocks, they help reduce dependency on fossil fuels and lower greenhouse gas emissions, thus aligning with the principles of green chemistry, particularly the use of renewable materials and the prevention of waste.

Water is another widely recognised green solvent due to its abundance, low cost, and non-toxic nature. It is often referred to as the "universal solvent" because of its ability to dissolve a wide variety of substances, making it indispensable in countless chemical processes (Queffelec *et al*., 2024). However, water's unique properties extend far beyond its solubility power. Its high heat capacity and polarity make it suitable for facilitating a range of chemical reactions, including hydrolysis, oxidation, and acid-base catalysis. In recent years, significant advances have been made in the field of aqueous-phase catalysis, where water acts as the solvent for chemical transformations, such as the production of fine chemicals and pharmaceuticals (Kokkinos & Zachos, 2024). Additionally, water's ability to form hydrogen bonds with solutes enhances its effectiveness as a medium for certain organic reactions, such as cycloaddition and condensation reactions. The environmental benefits of using water as a solvent are numerous, including the elimination of hazardous waste and the reduction of solvent emissions. However, the primary limitation of water is its polarity, which can restrict its use in dissolving non-polar substances, necessitating the development of innovative water-based reaction systems that can expand its applicability (Gholami *et al*., 2024).

Supercritical carbon dioxide ($scCO_2$) is another green solvent gaining popularity, particularly in the fields of extraction, catalysis, and material synthesis (Yıldırım *et al*., 2024). $scCO_2$ is carbon dioxide that has been compressed and heated beyond its critical temperature and pressure, allowing it to exhibit the properties of both a liquid and a gas. This unique state enables $scCO_2$ to dissolve a wide range of solutes while maintaining the low viscosity and high diffusivity of a gas. One of the most notable applications of scCO2 is in supercritical fluid extraction (SFE), where it is used to extract bioactive compounds from natural products, such as caffeine from coffee beans or essential oils from plants (Herzyk, Piłakowska-Pietras & Korzeniowska, 2024). Unlike conventional organic solvents, scCO_2 is non-toxic, non-flammable, and can be easily separated from the extracted product by simply reducing pressure, eliminating the need for energy-intensive purification steps.

Moreover, since scCO_2 is obtained from naturally occurring carbon dioxide, it is considered a renewable solvent. Its use helps mitigate environmental concerns associated with organic solvent waste and reduces the overall carbon footprint of chemical processes (Hadi & Rahman, 2024). Despite its many advantages, the primary drawback of scCO_2 lies in its inability to dissolve highly polar substances, which limits its applicability to certain types of reactions (Kang *et al*., 2024). Nonetheless, its use in green chemistry continues to expand, particularly in fields where clean, solvent-free processes are prioritised.

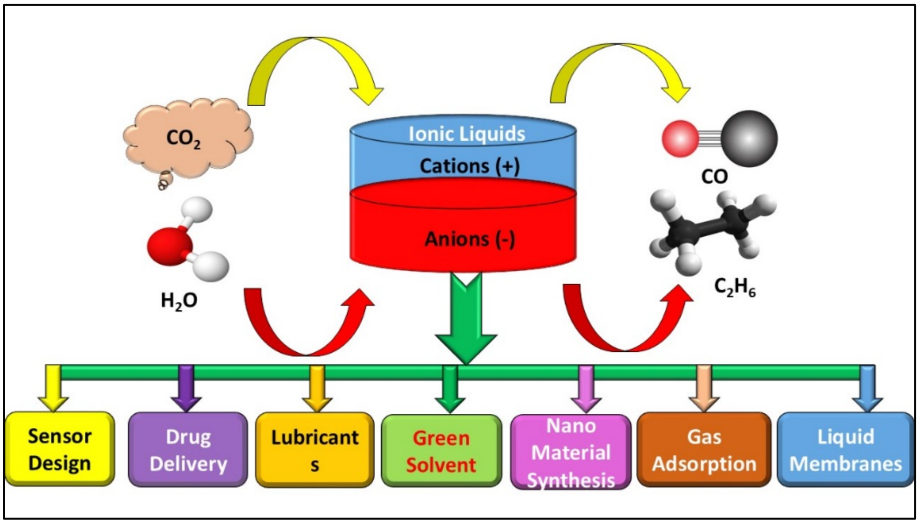

Figure 2: Schematic Drawing of Ionic Liquids and Their Applications *(Source: Author)*

Ionic Liquids, Deep Eutectic Solvents, and Fluorinated Solvents Ionic liquids (ILs) are salts in a liquid state, typically composed of large organic cations and smaller inorganic anions (Figure 2). Unlike traditional solvents, ionic liquids exhibit negligible vapour pressure, making them environmentally friendly due to the absence of volatile organic compounds (VOCs) (Gujjala *et al*., 2024). Additionally, their tunable properties—such as polarity, hydrophobicity, and viscosity—make them highly versatile solvents for a wide range of applications, including catalysis, separation processes, and electrochemical reactions (Li *et al*., 2024b). Ionic liquids have been particularly successful in facilitating reactions that involve difficult-to-handle reagents or products, such as in the synthesis of pharmaceuticals and the extraction of metals. Moreover, ionic liquids are often recyclable, allowing for their reuse in multiple cycles of a reaction without significant loss of performance (Shi *et al.*, 2024a).

However, despite their numerous advantages, the environmental profile of ionic liquids is still under investigation (Rothee *et al*., 2024). While they are considered green solvents due to their non-volatility, concerns have been raised about their biodegradability and long-term ecological impact. As such, ongoing research is focused on developing more sustainable ionic liquids with improved biodegradability and reduced toxicity.

Deep eutectic solvents (DES) are another class of green solvents that have gained attention due to their simplicity and eco-friendliness (Elhamarnah, Qiblawey & Nasser, 2024). DES is formed by mixing two or more components, typically a hydrogen bond donor and a hydrogen bond acceptor, which interact to create a eutectic mixture with a melting point lower than that of the individual components. Common DES components include choline chloride and urea, both of which are inexpensive and readily available. DES offers several advantages, including low toxicity, biodegradability, and the ability to dissolve a wide range of substances. They have been used in various industrial applications, such as metal recovery, biomass processing, and organic synthesis (Najaf-Abadi, Ghobadian & Dehghani-Soufi, 2024). One of the key benefits of DES is its ability to replace traditional solvents in environmentally challenging processes, such as the extraction of bioactive compounds from plants or the recycling of waste materials.

Furthermore, DES is often synthesised from renewable materials, aligning with the principles of green chemistry that emphasise the use of renewable feedstocks (Weerasinghe *et al*., 2024). However, DES still faces challenges related to their viscosity and thermal stability, which can limit their effectiveness in certain applications.

Fluorinated solvents, though not as widely recognised as other green solvents, play a significant role in specific applications, particularly in energy storage systems, such as lithium-ion batteries and supercapacitors (Molaiyan *et al*., 2024). These solvents are designed to be chemically stable, non-flammable, and capable of dissolving electrolytes without decomposing under extreme conditions. Fluorinated solvents, such as fluorinated ethers and perfluorocarbons, offer the advantage of low toxicity and high chemical resistance, making them suitable for use in harsh environments, including high-temperature and high-voltage applications (Shi *et al*., 2024b).

Additionally, their low global warming potential and low ozone-depleting potential contribute to their environmental credentials. In battery applications, fluorinated solvents help improve the stability and performance of the electrolyte, thereby enhancing the overall efficiency and lifespan of energy storage devices. However, the production and disposal of fluorinated solvents remain a concern, as they can be challenging to recycle and may pose environmental risks if not properly managed (Wang *et al*., 2024). Despite these challenges, ongoing research is focused on improving the sustainability of fluorinated solvents to further reduce their environmental impact.

Applications for Green Solvents in Chemical Processes

The transition towards sustainable chemistry has prompted a reevaluation of traditional solvent use across various chemical processes, leading to the adoption of green solvents (Figure 3) as viable alternatives (Lin *et al*., 2024). One of the primary applications of green solvents is in solvent extraction and separation processes, where they have been shown to offer significant advantages over conventional solvents (Shrivastav *et al*., 2024). Traditional solvents often pose health and environmental risks due to their volatility and toxicity, which can lead to hazardous waste and air pollution. Green solvents, on the other hand, provide a safer and more sustainable solution. For instance, bio-based solvents like ethyl lactate and glycerol have been successfully employed in the extraction of essential oils and natural products, offering lower toxicity and better biodegradability than their conventional counterparts. Additionally, the use of supercritical CO_2 in extraction processes eliminates the need for organic solvents entirely, minimising waste generation and facilitating easier product recovery. Studies have demonstrated that these green solvents can yield comparable or even superior extraction efficiencies, making them a preferred choice for industries aiming to reduce their environmental footprint.

In organic synthesis and catalysis, green solvents play a crucial role in enhancing reaction yields and selectivity. Traditional organic solvents often lead to undesirable side reactions and lower product purity, requiring extensive purification steps (Gao *et al*., 2023). Green solvents can improve the efficiency of reactions by providing a more suitable medium for reactants. For instance, water as a solvent has been used in several catalytic reactions, significantly improving yields and simplifying product isolation.

The use of ionic liquids in organic synthesis also exemplifies the benefits of green solvents, as they can stabilise reactive intermediates, leading to increased selectivity and reduced by-product formation. Moreover, the ability to tune the properties of ionic liquids allows chemists to design solvents that are specifically tailored for particular reactions, further enhancing the efficiency of organic synthesis (Mohammed, Hadrawi & Kianfar, 2023). The incorporation of green solvents in these processes not only improves economic viability by reducing costs associated with purification and waste disposal but also aligns with the principles of green chemistry by minimising hazardous substances (de Souza Mesquita *et al*., 2024).

Green solvents are also gaining traction in polymerisation and material synthesis, where they contribute to reducing volatile organic compound (VOC) emissions and producing more sustainable materials. Traditional solvents used in polymer production often emit VOCs, which pose significant health risks and contribute to environmental pollution. The adoption of bio-based solvents and supercritical fluids in polymerisation processes can significantly decrease or even eliminate VOC emissions. For example, bio-based solvents such as ethanol or bio-acetone have been employed in the synthesis of biodegradable polymers, enabling the production of eco-friendly materials with lower environmental impacts (Podapangi *et al*., 2023).

Additionally, supercritical CO_2 has been utilised in the polymerisation of various monomers, resulting in high-purity polymers without the need for toxic solvents. This not only reduces the environmental burden of polymer production but also enhances the sustainability of materials used in various applications, including packaging and construction (Hayes *et al*., 2022). The integration of green solvents into polymerisation processes thus represents a critical step toward more sustainable manufacturing practices.

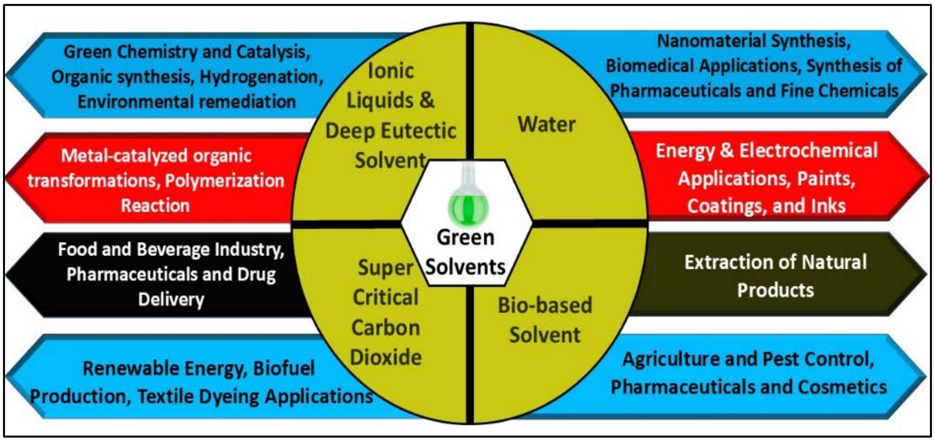

Figure 3: Schematic Representation of Different Green Solvents and Their Fields of Applications *(Source: Author)*

Cleaning and degreasing processes across various industries, including automotive and aerospace, are also increasingly adopting green solvents as effective alternatives to conventional solvents (Kanchana *et al*., 2024). Traditional cleaning agents often contain hazardous chemicals that can be harmful to both human health and the environment. Green solvents, such as terpenes, bio-based solvents, and ionic liquids, offer safe and effective cleaning solutions without compromising performance (Usman *et al*., 2023). For instance, citrus-based solvents have been employed in automotive cleaning applications, effectively removing grease and oil while biodegradable and non-toxic (Suri, Singh & Nema, 2021). In the aerospace industry, the use of supercritical CO_2 cleaning has gained traction as a method to clean complex components without the adverse effects associated with chlorinated solvents. These green cleaning agents not only meet regulatory requirements for reduced VOC emissions but also enhance workplace safety for employees. By replacing hazardous traditional solvents with green alternatives, industries can significantly improve their environmental profile while maintaining operational efficiency.

The pharmaceutical and agrochemical industries have also embraced the use of green solvents in their synthesis processes, leading to numerous advantages, including regulatory compliance and improved safety profiles (Dutta *et al*., 2022). The increasing pressure from regulatory agencies to minimise the use of hazardous substances has propelled the adoption of green solvents in these sectors. Case studies demonstrate that the integration of bio-based solvents and other green alternatives has led to more efficient synthetic routes and reduced environmental impacts. For example, the synthesis of active pharmaceutical ingredients (APIs) using water or bio-based solvents has been shown to enhance product purity while reducing toxic waste generation (Schenck *et al*., 2024). Additionally, the use of ionic liquids in agrochemical formulations has enabled the development of safer and more effective pesticides with lower environmental persistence. These advancements not only comply with regulatory standards but also align with the industry's commitment to sustainable practices. The incorporation of green solvents in pharmaceutical and agrochemical synthesis exemplifies how the principles of green chemistry can be effectively applied to reduce the environmental footprint of chemical production while maintaining product quality and safety.

Designing Green Reaction Media

The design of sustainable reaction media is crucial in enhancing reaction rates, efficiency, and selectivity in chemical processes (Ahmed *et al*., 2023). Traditional solvents often hinder reaction performance due to their toxicity, volatility, and environmental impact, necessitating the search for greener alternatives. Green reaction media not only reduce the environmental footprint but also improve the efficiency of chemical reactions by providing more favorable conditions for reactants. For example, water as a reaction medium has been widely recognized for its ability to facilitate numerous reactions due to its unique properties, such as high polarity and ability to solvate a wide range of organic and inorganic compounds. By utilising green solvents or solvent systems that are less toxic and more biodegradable, chemists can optimize reaction conditions while simultaneously addressing environmental and safety concerns. The shift toward green reaction media is aligned with the principles of green chemistry, which advocate for the design of processes that minimize waste and hazardous materials while enhancing the overall sustainability of chemical production (Martinengo *et al*., 2024).

Solvent-free systems represent a promising approach to green chemistry, offering significant advantages but also posing certain challenges (Castiello *et al.*, 2023). In solvent-free reactions, the absence of traditional solvents can lead to higher reaction rates and improved selectivity due to increased concentrations of reactants. These systems often simplify the purification processes, as there is no solvent to remove, reducing waste and resource consumption. However, implementing solvent-free systems can also present challenges, such as difficulties in controlling reaction temperature and managing heat transfer, particularly in large-scale processes (Chen, Tariq & Gu, 2024). Some reactions may also require solvents to dissolve reactants or facilitate specific reaction mechanisms, making it essential to evaluate the compatibility of solvent-free systems with various types of reactions. Despite these challenges, the exploration of solvent-free systems is gaining traction, with many researchers demonstrating successful applications across a range of chemical transformations, further reinforcing the feasibility of this approach in sustainable chemistry.

Aqueous systems and other environmentally benign solvents have emerged as key components in the design of green reaction media, offering a variety of advantages in chemical processes. Water, as a universally accepted solvent, provides a safe and non-toxic alternative that enhances reaction kinetics and selectivity for many organic reactions, including substitutions, oxidations, and reductions. Other environmentally benign solvents, such as bio-based solvents and ionic liquids, have also been extensively researched and applied in various chemical transformations. For instance, ionic liquids have been recognized for their unique properties, such as low volatility and tunable polarity, making them effective for a wide range of applications, from catalysis to extraction processes. Several case studies highlight the successful use of these green reaction media in industries such as pharmaceuticals, where water and ionic liquids have been utilized to synthesize complex compounds with improved yields and reduced environmental impacts (Costa, Forster-Carneiro & Hallett, 2024). These advancements underscore the importance of designing reaction media that not only meet the demands of modern chemistry but also align with the principles of sustainability, ultimately leading to safer and more efficient chemical processes that benefit both industry and the environment.

Challenges in Implementing Green Solvents

Despite the numerous advantages of green solvents in promoting sustainable chemical processes, several challenges hinder their widespread adoption in industry (Qiao *et al*., 2024). One of the primary barriers is the scalability and cost-effectiveness of these alternatives. While many green solvents demonstrate favourable environmental profiles and safety benefits in laboratory settings, scaling up these processes for industrial applications often proves difficult (Amani *et al*., 2024). The synthesis of green solvents can sometimes involve higher costs and complexities compared to conventional solvents, which are often derived from established processes and readily available fossil fuels. Additionally, industries frequently operate under tight profit margins, making the transition to greener alternatives financially challenging. Without significant economic incentives or regulatory pressures, companies may hesitate to invest in new technologies or change their established practices. Consequently, achieving large-scale implementation of green solvents necessitates not only further research into cost-effective production methods but also potential government support through subsidies, tax incentives, or stringent regulations on hazardous solvents (Lau *et al*., 2024).

Another significant challenge in the transition to green solvents lies in the limited availability of alternatives for specific chemical reactions that still depend on hazardous solvents (Ramos-Villaseñor, Sartillo-Piscil & Frontana-Uribe, 2024). Many traditional solvents, such as chlorinated hydrocarbons or aromatic hydrocarbons, possess properties that are difficult to replicate with green alternatives, resulting in certain reactions remaining reliant on these toxic substances. Moreover, there are still many chemical processes for which suitable green solvent replacements have not yet been developed, creating a gap that hampers the complete adoption of sustainable practices (Mainkar, Ray & Chandrasekhar, 2024). This situation highlights the need for further research to identify and design novel green solvents with tailored properties that can meet the diverse requirements of various reactions. To bridge this gap, collaborative efforts among academia, industry, and regulatory bodies are essential to accelerating the discovery and optimisation of green solvents. By focusing on developing solvents that can perform similarly or even outperform traditional solvents while minimising environmental impacts, the chemical industry can move closer to achieving a more sustainable and responsible approach to chemical manufacturing.

Future Perspectives and Research Directions

The future of green solvents and sustainable practices in the chemical industry hinges on innovation, education, and collaboration. Advances in solvent synthesis are crucial, focusing on the development of novel green solvents from renewable sources, which can replace hazardous traditional solvents. Researchers are increasingly exploring bio-based materials, waste feedstocks, and eco-friendly processes to create solvents with desirable properties that cater to various chemical reactions. Additionally, integrating green chemistry principles into educational curricula is paramount to fostering a generation of chemists equipped with the knowledge and skills to prioritise sustainability in their work. This educational shift will not only enhance awareness but also inspire innovative thinking among future scientists and engineers. Collaboration among academia, industry, and government entities is essential to drive the adoption of sustainable practices and ensure that research translates into practical applications. By working together, these stakeholders can facilitate the sharing of knowledge, resources, and best practices to overcome barriers to the widespread implementation of green solvents. Furthermore, technological advancements, including the development of smart reaction systems and process intensification techniques, hold the potential for breakthroughs in green chemistry. These innovations can streamline chemical processes, enhance efficiency, and reduce waste generation, making sustainable practices more attractive and feasible for industries. Ultimately, by focusing on these key areas, the chemical industry can move towards a more sustainable future, minimising environmental impact while ensuring safety and efficiency in chemical processes.

Conclusion

In conclusion, the transition to green solvents and reaction media represents a pivotal shift towards more sustainable chemical processes that can significantly mitigate environmental risks. The key benefits of adopting green solvents include reduced toxicity, a lower environmental impact, and the use of renewable resources, which collectively contribute to minimising pollution and promoting safer working conditions in the chemical industry. By replacing conventional solvents with environmentally friendly alternatives, companies can enhance the overall sustainability of their operations while adhering to increasing regulatory demands and consumer expectations for greener practices. However, the importance of continuous innovation and research cannot be overstated; ongoing efforts to develop novel green solvents with tailored properties are crucial for expanding the range of applications and addressing the specific needs of various chemical processes. Furthermore, as the chemical industry faces mounting challenges related to resource depletion and climate change, it is imperative to embrace a paradigm shift towards greener processes that prioritise environmental stewardship. This transition not only aligns with global sustainability goals but also positions the industry as a leader in responsible innovation. By investing in research, fostering collaboration among academia, industry, and regulatory bodies, and integrating green chemistry principles into education, the chemical sector can pave the way for a more sustainable future. The commitment to adopting greener solvents and reaction media will ultimately lead to enhanced efficiency, reduced waste generation, and a more harmonious relationship between chemical production and the environment, ensuring that future generations inherit a healthier planet.

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