OPEN ACCESS

Haya: The Saudi Journal of Life Sciences

Abbreviated Key Title: Haya Saudi J Life Sci
ISSN 2415-623X (Print) | ISSN 2415-6221 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Review Article

Granted Patents Related to Green Solvents: A Review

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DOI: https://doi.org/10.36348/sjls.2025.v10i03.003 | **Received:** 28.01.2025 | **Accepted:** 04.03.2025 | **Published:** 12.03.2025

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Abstract

The review focused on recent patents between 2018 and 2023 that concern the use of green solvents that are relevant to the development of bio-based solvents, ionic liquids, deep eutectic solvents and supercritical fluids. It draws on data from global databases to identify progress toward sustainability, safety and industrial efficiency with reduced environmental impacts. The patents are categorized according to their type, applications and innovation, thereby highlighting emerging trends, research gaps and the role of intellectual property in driving sustainable chemistry solutions. Essentially, among other principles of green chemistry and circular economy, they are identified on the basis of their low toxic effects, biodegradability and renewable sourcing. These green solvents, however, are greener alternatives to more conventional petrochemical-based solvents in pharmaceutical, agrochemical, cosmetic, and other applications. A number of recent patents on chemical synthesis, extraction, and cleaning technologies highlight the environmental and industrial advantages of green solvents. This will consist of activity-specific ionic liquids, scalable bio-derived solvents and extremely efficient solvent recovery systems for improving the efficiency and sustainability of chemical processes. Despite challenges like cost, scalability and performance limitations, patents demonstrate opportunities to improve synthesis methods, develop multifunctional applications, and integrate green solvents into existing industrial systems. This review emphasizes the transformative potential of green solvents in fostering environmental sustainability and supporting a circular economy. Green solvents are helping reshape industrial practices and reduce toxic petrochemical solvent reliance while addressing global environmental and regulatory challenges.

Keywords: Deep Eutectic Solvents, Green Solvent, Ionic Liquids, Patent, Supercritical Fluid, Waste Biomass.

INTRODUCTION

According to de Marco *et al*., (2018), green chemistry as first popularised by Paul Anastas and developed by John Warner in the 1990s, constitute a unique and sustainable way of producing chemicals that reduces the possible harmful substances (from synthesis to use and disposal). As they are biodegradable and have lesser toxicity and usually originate from CO_2 sources, green solvents represent a more environmentally friendly solvent than conventional solvents. Fundamentally, green chemistry emerged at least to attenuate the environmental effects of chemical processes. The inclusion of green solvents allows for less reliance on volatile chemicals, less hazardous waste production and aligns with greater principles of sustainable chemistry in search for industrial processes that are bounty to the environment (Anastas & Warner, 1998). As a result of the worldwide push for sustainability, sectors like cleaning goods, agrochemicals and pharmaceuticals depend on green solvents as a necessity for sustainability from the drive towards greener processes and environment-friendly compliance with stringent environmental requirements (Patil *et al*., 2021).

As it stands, the foundational framework of green chemistry is built upon 12 core ideas that is premised on creating safer chemicals that minimise waste, increase energy efficiency and halt pollution at its source (Martinengo *et al*., 2024). In essence, with the combination of these relevant ideas, green chemistry is saddled with the potential to provide ecologically responsible and financially feasible substitutes for traditional chemical processes in particular sectors the encompasses manufacturing, agriculture and pharmaceuticals (Chen *et al*., 2020). Utilizing renewable feedstocks, optimizing energy efficiency, and reducing reliance on hazardous materials like heavy metals are the

key components of green chemistry, which aims to reduce the environmental effect of chemical manufacturing (Ruiz-Mercado *et al*., 2016). Innovations in catalysis and bio-based materials further enhance process efficiency and sustainability, enabling safer industrial practices. The planet's health and global economy are improving as a result of green chemistry's clear path to long-term solutions to significant environmental issues including pollution and climate change (Chu *et al*., 2016). Since they are utilized as substitutes for traditional solvents, the majority of which are hazardous, flammable and non-renewable fossil fuels, green solvents are especially significant. Simplistically, this implies that integrating green solvents in diverse ways within the framework of industries translates to reducing their ecological footprints to a great degree without any sort of compromise on their functional efficiencies (Basahel *et al*., 2018). While this is so, green solvents have overly been presented as one support that may reduce pollution and result in resource conservation for the purpose of shifting to more environmentally friendly practices by industry. Significantly, over the last couple of years, the development and commercialization of green solvents commenced. To be precise, some of the bio-based solvents such as ethyl lactate, glycerol and DMC were already being applied in a series of industries from food processing to pharmaceuticals (Zhao *et al*., 2019). In the same vein, other essential developments that included ionic liquids and deep eutectic solvents became popular due to their tunable nature and low environmental impact (Basahel *et al*., 2018). To add to this development was the noticeable rising interest in green solvents that reflected in the number of granted innovative solvent technology patents. Basically, these patents characterized the development in synthesis and application of green solvents, mainly in sectors such as solvent extraction, catalysis and industrial cleaning (Patil *et al*., 2021). Most notably, a patent of this nature highlights a growing market for green solvents themselves and their potential to drive the next wave of innovation in sustainable chemistry.

The use of patents to encourage innovation in green chemistry constitutes a bio-innovative way of safeguarding the environment. This is the case because it can support environmentally friendly technologies such as green solvents. Moreover, they allow inventors exclusive rights for a period of 20 years that ends up attracting investors to research and development towards gaining competitive edges (Björklund *et al*., 2020). Mostly through the cooperation of the researchers, companies and governments with patents have become commercialized through sustainable solutions (Fournier *et al*., 2016). Green solvents that require significant research and development (R&D) that seem to benefit from patent protection, enabling safer and greener alternatives to conventional chemicals and driving further advancements in sustainable practices. Meanwhile, patents protect innovations in green solvents that are vital for finding alternatives in industries such as pharmaceuticals and agrochemicals. This is because they provide exclusive rights to the inventors for commercialization and protection of intellectual property (WIPO, 2021). Although, patent filings tend to cover formulations, production methods and efficiency improvements, while offering insights into research trends (Aoki *et al*., 2020). In this regard, the main subjects of patenting are bio-based solvents, ionic liquids, supercritical fluids and deep eutectic solvents towards guaranteeing advancement toward safer, biodegradable, high-performance industrial solutions while decreasing environmental and health risks.

In this light, the present review examined recent patents on green solvents for the purpose of pointing out trends, innovations and advancements in performance, cost, as well as scalability challenges. Also, it explored the breakthroughs that drive sustainability, identifies research gaps and emphasizes the role of patents in advancing green chemistry and reducing industrial environmental impacts.

Scope of the Review

Importantly, the present review cut across patent reviews on green solvents that were granted between 2018 and 2023. So, in order to conduct a comprehensive international overview, immense sourcing was done from major global databases like the United States Patent and Trademark Office (USPTO), European Patent Office (EPO), World Intellectual Property Organization (WIPO) and Japanese Patent Office (JPO). This covered vital aspects of bio-based solvents like ethyl lactate and bioethanol, ionic liquids known for non-volatility and versatility, deep eutectic solvents with benign environmental properties, supercritical fluids like supercritical CO_2 and new green solvent formulations. These patents have been implicated to satisfy the demand for sustainable alternatives to petrochemical-based solvents, with a guarantee of lesser environmental impact, higher safety and efficiency in industries. It also reviews the industrial application of these technologies in relation to how they contribute to developments in sustainable chemistry through minimization of industrial footprint and process safety. Through trend and innovation analysis, it sets out the commercial implications of the future role that may be played by green solvents in facilitating greener industrial practices and the attainment of sustainability goals (McMurray *et al*., 2021).

METHODOLOGY

Patent Search Strategy

It suffices to state that the methodology applied in this review was structured to holistically capture recent granted patents that are related to green solvents. Essentially, the systematic approach that was adopted was targeted at ensuring relevance in the selection of patents in line with certain criteria that were representative of the continuous development taking

place in the area. So, the search strategy incorporated the use of multiple databases that were widely recognized for documentation of patent.

Databases Used for Patent Search

Databases used for the patent search were obtained from multiple patent databases. This was essential to providing an international perspective with consideration to the most relevant patents in the green solvent domain. Precisely, the highlighted databases offered extensive access to granted patents and applications which gave a comprehensive overview of the recorded advancements in green solvent technologies. The search was started with Google Patents which is adjudged to be a free Patent and Prior Art Search that is based on filings in some jurisdictions like the United States and Europe. The results were further subjected to examination in the USPTO database for the purpose of providing specific and detailed information regarding the United States granted utility and process patents, including those of chemicals and solvents in particular. Also, the search was extended to the WIPO database for Patent Cooperation Treaty (PCT) applications. The purpose was to enable a thorough overview of novelty that covered several jurisdictions. Moreover, the EPO database was further utilized in the identification of European patents that encapsulated immense technological advancement within the European Union. Taken together, these resources ensured that a thorough and internationally representative review was conducted.

Search Keywords and Criteria

Basically, the overall search was done in such a way as to ensure that the relevant patents that concern green solvents could be captured, including several aspects of their development regarding environmental properties, sources and industrial applications. The following keywords were used appropriately: "green solvents," "sustainable solvents," "biodegradable solvents," "renewable solvents," "eco-friendly solvents," "nontoxic solvents," "ionic liquids," "supercritical fluids," "deep eutectic solvents," and "solvent replacement." To obtain a broad variety of patents pertaining to green solvent technologies from their chemical makeup and manufacturing processes to their applications across several industries, these phrases have been strategically combined. Boolean operators like AND, OR and NOT were employed to further refine the search, allowing for precise alterations in either narrowing or widening the search's scope. In adopting this methodology, a thorough targeted selection of patents that satisfied the inclusion criteria of the study which offered a thorough analysis of pertinent advancements in the field was guaranteed.

Inclusion and Exclusion Criteria

As it concerns the current review, the duration of time considered for the patent grant ranged from 2015 to 2024. This was to enable proper focus on more recent and relevant technological innovations in green solvents. Again, the time frame was targeted at capturing current trends that reflect recent industrial demand for newer and more environmentally friendly green solvents. Moreover, the range of time, which is from 2015-2024 reflected those years in which the area of renewable and green solvent technologies was bound to undergo some developments as a result of the growing global emphasis on sustainability in chemical processes.

Types of Patents Included

Primarily, the patents selected for this review were focused on utility and process patents because they constitute the most relevant to the development and industrial application of green solvents. However, utility patents were examined for their emphasis on modern inventions that offer functional benefits that cut across innovative green solvent formulations or compositions. Practically, these patents tend to provide critical information on the unique environmental advantages of green solvents in comparison to traditional alternatives. On the other hand, the process patents entail novel or improved methods for producing green solvents or utilizing them in industrial applications. Essentially, these patents are relevant for understanding the technologies that underpin the synthesis and large-scale implementation of green solvents across industries like pharmaceuticals, food processing and cleaning. Moreover, other patent types, such as design patents or those focusing solely on chemical structures were removed from the review. This was hinged on the fact that they lack direct relevance to the functional or process-driven advancements in green solvent development.

Data Analysis

In the course of the review, data obtained from the patent search were subjected to rigorous analysis that followed a well-structured pattem towards identifying some of the major trends, technological advances and patterns related to green solvent development. In addition, the analysis examined categories of patents in several key dimensions that included solvent type, applications and the nature of innovation. This approach helped to ensure a thorough understanding of the evolving landscape of green solvents and the patents that are driving these innovations. The assessment of granted patents combined qualitative and quantitative methods. Qualitative analysis was carried out to examine patent claims and descriptions towards identifying innovations in solvent formulations, production processes and applications. For the quantitative analysis, statistical tools were employed to track trends in patent filings, geographical distribution and major assignees. This mixed-methods approach provided comprehensive information on technological advancements and broader trends in green solvents.

Review Outcomes

Characteristics of Green Solvents

Observably, one important feature of the green solvents is hinged on their low toxicity which makes them safe for the environment as well as living things in general or humans in particular. Despite this, green solvents are also very nontoxic as opposed to general solvents containing toluene and benzene, which reportedly contribute to neurotoxicity among humans and increase the risks for cancer. These include the bio-based alcohols, bio-alcohol and esters, such as ethyl lactate, which are traditional examples of green low-risk solvents that can be handled and disposed of more safely with attendant reduction of environmental and occupational exposure (Zhao *et al*., 2019; Patil *et al*., 2021; Li *et al*., 2024). Additionally, these green solvents are pertinently recognized for their recyclability, which happens to be a key characteristic that contributes to their activity in reducing waste and supporting circular economy practices (Peeters *et al*., 2022). Another critical attribute of green solvents is premised on their biodegradability. Unlike traditional solvents that often fail to decompose naturally and result in persistent environmental contamination, green solvents are designed to degrade into non-toxic byproducts that by extension limit their harmful effects on soil and water systems. Some biodegradable examples like bio-based solvents such as glycerol and terpenes are preferred in industries where environmental sustainability is of essence (Ochoa *et al*., 2020; Ullah *et al*., 2024). These green solvents primarily originate from renewable feedstock, such as biomass, agricultural waste and plant oils. Unlike petroleum-based solvents which are largely dependent on finite resources that contribute to their depletion, green solvents are renewable. The bio-based solvents like dimethyl carbonate (DMC) and ethyl lactate are made from renewable crops or by-products, which has the potential to depict the sustainable approach of the chemical industry. This dependence on renewable feedstock not only drives sustainability in the production of such solvents but also adheres to the key principles of the circular economy, which encourage the thoughtful use and valorization of waste for providing value-added commodities (Ragauskas *et al*., 2014; Klemmer *et al*., 2018; Calvo-Flores *et al*., 2018).

Remarkably, the environmental impact of green solvents is notably lower than that of conventional alternatives throughout their lifecycle spanning from synthesis to disposal. Following this, their production often requires less energy and generates fewer harmful emissions. Many green solvents are also non-volatile which make them capable of reducing air pollution and their overall environmental footprint. Sustainable sourcing and efficient recycling or reuse further enhance their eco-friendly profile (Basahel *et al*., 2018; Richie *et al*., 2024). Despite their environmental benefits, green solvents do not compromise on performance. Most of them function as well or even better compared to their conventional counterparts. For example, supercritical CO_2 serves as an effective green solvent in the extraction of natural products by selectively dissolving target materials while leaving other components in their original state, hence offering a feasible environmental-friendly substitute for conventional organic solvents. Moreover, most green solvents have beneficial properties, for example, high solvating power-which, in fact, makes them efficient in a variety of types of chemical reactions and industrial processes (Verde *et al*., 2020; Patil *et al*., 2021). The final key characteristic of green solvents pertains to their VOC-emission-free nature. Typical organic solvents, such as xylene and acetone, are VOC-emitting. However, these VOCs further cause air pollution and are responsible for smog formation. Green solvents, such as ionic liquids and DES, do not emit harmful VOCs; thus, this gives them a considerable edge in industries related to coatings, cleaning products and adhesives. Finally, green solvents are generally less flammable, hence improving safety during handling and reducing the risk of accidents in industrial or laboratory settings. Based on the foregoing, these solvents reduce environmental harm by improving air quality, while underlining the value of adopting sustainable alternatives in various applications (Zhao *et al*., 2019; Winterton *et al*., 2021; Citarella *et al*., 2022; Hu *et al*., 2024).

The Role of Green Solvents in Sustainable Chemistry

Reportedly, green solvents have emerged as the most integral part of green chemistry. This is hinged on the grounds that greener alternatives are increasingly being substituted for conventional petrochemical-based solvents. However, the ever-increasing importance placed on it is due to the increasing need for greener industrial practices that guarantees a reduced level of environmentally related hazards. Green solvents are to be designed according to the twelve principles of green chemistry that anchors on minimal hazardous substances, renewable materials and process efficiency. These principles as defined by Paul Anastas and John Warner, form the fundamental basis for designing safer and more sustainable chemical processes that offer considerably low impact on human health and the environment, as stated by Clarke *et al*., (2018). Since the United Nations launched the Sustainable Development Goals in 2015, the requirement for greener practices in many industries elevated the importance of green solvents. Nowadays, green solvents are considered among the major solutions that reduce the ecological footprint of industrial operations. This is due to the greater demand for sustainable chemistry, encouraging industries toward using cleaner and safer alternatives to traditional chemical processes (Morton *et al*., 2017). On the other hand, there are many benefits for the environment once green solvents are used industrially. These include drastically reduced waste, a lower emission level and minimal dependence on non-renewable resources that are all realized as a result (Anastas & Warner, 1998). Green solvents will also increasingly support the development of a circular

economy whereby waste products become reused or reprocessed into material valuables. The use of green solvents has been increasingly important in industries such as pharmaceuticals, agrochemicals, and food processing. In these industries, the use of green solvents can enhance safety, efficiency, and sustainability. For example, the use of CO_2 as a green solvent in extracting essential oils and pharmaceuticals has been one of the successful methods that reduce harmful organic solvents (Verde *et al*., 2020). Besides, green solvents can enable the processes of extraction in a cleaner and economic way.

Historically, the chemical industry has heavily relied on volatile organic compounds (VOCs), which are known for their toxicity, flammability, and environmental hazards. In response to growing regulatory pressure and public awareness, green solvents have gained traction as a safer and more sustainable alternative (David & Niculescu, 2021). They are characterized by their lower toxicity, biodegradability and derivation from renewable resources, such as agricultural by-products. To minimize pollution and long-term environmental impact, green solvents have been designed. However, as a result of its flexibility, it is applied extensively in various fields-including the pharmaceutical, cosmetic and cleaning agent fields (Welton, 2015). With companies now facing more stringent environmental regulations and consumers demanding more environmentally friendly products, green solvents can be expected to become increasingly adopted in the future, with a role in sustainable industrial processes in the long run (Winterton *et al*., 2021).

Types and Classifications of Green Solvents

Green solvents have become a central topic in the field of sustainable chemistry, particularly due to their ability to replace conventional organic solvents that are often toxic, non-biodegradable and derived from fossil resources. Green solvents are typically classified based on their environmental advantages, such as low toxicity, biodegradability and renewability (Welton, 2015; Clark *et al*., 2015; Winterton, 2021). This section covers the various types of green solvents with respect to recent developments and granted patents, which in turn shows a growing interest in eco-friendly alternatives.

A) *Renewable Solvents:*

These are bio-sourced solvents that are obtained from waste plant materials. Bio-based solvents are sourced from biological material which is renewable, for example, from plants, algae, and waste, thereby posing an attractive alternative to traditional petrochemicals solvents. Such solvents are sustainable and also have low toxicity enabling them to create less pollution. The most common bio-solvents include ethanol, glycerol, and bio-esters derived from corn, sugarcane and agricultural waste. This category of solvents can be found in several industries like pharmaceuticals, cleaning, food processing. In the past few years, many patents have been issued on the topic of manufacturing bio-solvents intended to replace their fossil-based counterparts as follows. One recently granted patent US20200215038A1 is related to the development of bio-based solvents derived from glycerol, which is a non-edible product from biodiesel production, and it was registered in 2020. This invention also describes that glycerol esters are suitable as a less toxic, eco-friendly solvent in industrial cleaning and extraction processes. Another success story is the European patent EP3573518A1 issued in 2021. It includes the preparation of lignocellulosic waste material to bio-based solvents.

These solvents, obtained from renewable plant oils, have low toxicity; hence, they are especially suitable in drug formulations. These patents underline the attention being devoted to bio-based solvents and new methodologies for their development from renewable resources in a sustainable way.

B) Ionic Liquids and Deep Eutectic Solvents:

Ionic liquids (ILs) and deep eutectic solvents (DES) have been regarded as the next generation of green solvents due to their unique properties. ILs are salts that are liquid at relatively low temperatures (below 100°C) and characterized by non-volatile nature, excellent solvating ability, and low flammability (Thomas & Marvey, 2016). DESs, in turn, are combinations of at least two elements which, by interacting with each other, provide a eutectic system with a melting point lower than its pure components' (Abranches *et al*., 2023). Both ILs and DES share several benefits over conventional solvents, such as wide dissolution capacity, low vapor pressure, and biodegradability. Moreover, they can be synthesized from renewable resources, hence making them eco-friendly alternatives. A number of patents have been granted on ILs and DES in recent years, showing the latest developments regarding their synthesis methods, stability, and industrial applications. One of the significant developments is presented in Patent US10544323B2 of the year 2020, which presents a new class of ionic liquid as an effective green solvent for carbon capture processes. It is prepared from choline chloride and an organic acid, hence presenting an environmentally friendly alternative with a view to reducing the footprints of CO_2 capture technologies. Another considered patent is WO2020143701A1 (2020); this describes a procedure for the preparation of DES from renewable raw material sources, plant-based acids, and alcohols. The resultant DES solvents are used in pretreatment biomass and waste recycling for circular economy compliance. Patent EP3653019A1 (2020) describes the use of DES for the extraction of valuable metals from WEEE. This DES, prepared by mixing choline chloride and urea, offers a greener and more efficient alternative to conventional extraction processes. These patents together show the advancing role of ionic liquids and deep eutectic solvents in green chemistry, in

relation to the protection of the environment and the new approaches to waste management.

C) *Supercritical Fluid Solvents*:

Supercritical carbon dioxide ($scCO_2$) is regarded by some as the most environmentally benign liquid since it is non-poisonous, non-flammable and the ecological effect is minimal (Poliakoff & Licence, 2015). These fluids, when in a supercritical condition, showcase exceptional solvent characteristics, allowing them to dissolve not only non-polar but also polar substances, which makes them very useful in an assortment of extraction and separation operations. For example, supercritical CO_2 is widely used as a solvent for essential oil, flavour and active ingredients for drugs, foods, and cosmetics without the use of toxic organic solvents. The use of supercritical CO_2 as a green solvent has already been patented, including the emulsion extraction technology for supercritical fluids, which is expected to see even wider applications in sustainable development. One of the patents is US11062638B2, 2021, which describes a method of extraction of bioactive compounds from plants using supercritical carbon dioxide without using harmful organic solvents. Therefore, it provides a cleaner and greener alternative for compound extraction. Another development of interest is that related to a novel supercritical CO_2 based process for the extraction of high-value compounds from waste biomass and is covered under Patent WO2020072341A1, 2020. This is an environmentally friendly approach since it eliminates the use of organic solvents and considerably reduces the generation of waste. Patent US10646761B2 (2020) illustrates the application of supercritical CO_2 in the manufacture of pharmaceutical-grade compounds. It presents a process that enhances $scCO_2$ extraction efficiency while reducing the associated carbon footprint from the process. These patents indicate the increasing importance of supercritical CO_2 as an environmentally friendly solvent in processes for extracting valuable compounds, proving its potential for the sustainable use of natural resources and waste materials.

D) Waste Biomass Solvents:

At present, waste-derived solvents are gaining much attention. In particular, the ones from lignocellulosic biomass-agricultural residues, wood and paper wastes-have a potential role as sustainable alternatives to conventional solvents. Lignocellulosic biomass is one such abundant, renewable feedstock that can be transformed into a variety of solvents that include alcohols, esters and other bio-based solvents. The conversion of waste biomass into useful solvents supports the philosophy of a circular economy which highlights converting waste to valuable resources, reducing dependency on petrochemical solvents. Recent innovations in green chemistry have focused on developing methods to convert waste biomass into sustainable solvents, significantly improving the efficiency of these processes. A key example includes Patent US10359524B2, 2019, depicting a catalytic process for lignocellulosic biomass into green solvents. These have been further utilized in the biofuel production stage, proving a sustainable process in environmental aspects as well. Another recent one is covered by European Patent number EP3438129A1 of 2020, titled "Bio-based Solvents from Waste Paper and Agric Residues." These biodegradable solvents find applications in cleaning and degreasing, representing an environmentally friendly alternative to traditional chemical solutions. Patent WO2020225130A1, in the year 2020, presents a new approach to the utilization of waste-derived solvents for the extraction of valuable compounds from algae. This process employs solvents produced from lignocellulosic biomass and, therefore, represents an environmentally sustainable method for algal biomass processing. Taken together, these patents indicate the transformative power of waste-based solvent systems as eco-friendly alternatives to petrochemical-based solvents and hence reduce the production of wastes, ensuring efficient recovery.

E) Water as an Ecological Solvent:

Water is considered an environmentally benign solvent since it is nontoxic, plentiful and biodegradable. In green chemistry, water has become a significant solvent in conducting chemical processes like catalytic reactions, extraction and synthesis of green chemicals. These water-based solvent systems are increasingly being developed to replace organic solvents in industries such as pharmaceuticals, agrochemicals and food processing (Lajoie *et al*., 2022). As highlighted by several key patents, recent advancements in water-based solvent systems have led to innovative applications in various industrial processes. A significant example is seen with patent US10502987B2 of the year 2019, that focuses on using water-based solvents for pharmaceutical synthesis. Instead, it has presented a greener drug-manufacturing technique by replacing organic solvents in the process, which is less harming to the environment. Another invention disclosed in the Patent WO2020024893A1 developed in 2020, relates to a water-based solvent system for the extraction of bioactive compounds from plants. This invention has shown improved efficiency in extraction without compromising the goal of sustainability, thus demonstrating its promise in natural product processing. Aside that, Patent US10250363B2 (2019) revealed a method that employed water as a solvent in the synthesis of biodegradable polymers. The approach reduces the ecological footprint of polymer production, thereby making it of great value for green manufacturing. These patents reflect the continuous efforts to refine water-based solvent systems towards laying emphasis on the central role of water in advancing green chemistry and fostering sustainable industrial practices.

Applications of Green Solvents

Green solvents have been implicated to be finding widespread applications across various industries and processes (Ullah *et al*., 2024; Kosmalski *et al*.,

2022). Some of these applications of green solvents are in chemical synthesis, extraction processes and cleaning and degreasing.

A) Chemical Synthesis:

Regarding chemical synthesis, green solvents are playing increasingly vital role in organic synthesis that make them suitable replacement for those traditional harmful organic solvents. These eco-friendly alternatives provide a more sustainable medium for conducting chemical reactions, reducing the environmental impact associated with conventional solvents (Qareaghaj *et al*., 2024). Not only do they contribute to a safer and cleaner process, but they also frequently match or even surpass the reaction efficiency of their more hazardous counterparts. This implies that by offering comparable or improved reaction outcomes, green solvents help promote greener chemistry without compromising performance. This makes them a valuable tool for advancing sustainable industrial practices (Welton *et al*., 2015).

B) Extraction Processes:

Green solvents are largely employed in the process of extraction, with particular reference to the food and pharmaceutical industries (Chemat *et al*., 2019). These environmentally friendly solvents tend to provide a safe and more sustainable alternative to traditional extraction methods which often rely on toxic and volatile organic compounds. Green solvents enable the efficient extraction of valuable compounds from natural sources, such as plant materials, without the harmful environmental and health impacts typically associated with conventional solvents. Their use not only reduces the risk of contamination in products like essential oils, bioactive compounds and nutraceuticals, but also enhances the overall sustainability of extraction techniques. Notably, this shift toward greener extraction processes has become relevantly crucial for industries that are focused on safety, environmental responsibility and high-quality production standards (Chemat *et al*., 2019; Tzanova *et al*., 2024).

C) Cleaning and Degreasing:

It is worthy to note that these green solvents are becoming increasingly popular for cleaning and degreasing applications, which in turn provide a more environmentally responsible alternative to traditional solvents that often carry significant environmental and health risks (Ramamoorthi *et al*., 2020). These eco-friendly solvents are very effective at removing oils, grease and other contaminants from surfaces, equipment and machinery without relying on the harsh chemicals that are commonly found in the conventional cleaning agents. It therefore means that by minimizing the release of volatile organic compounds (VOCs) and other hazardous substances into the environment, green solvents potentially contribute to improved air and water quality. Particularly, the adoption of green solvents is important in industries such as automotive, manufacturing and aerospace, where cleaning and degreasing are essential processes. In addition to reducing the environmental footprint, green solvents often improve workplace safety by lowering the risk of exposure to toxic chemicals, thereby making them a valuable solution for sustainable industrial maintenance and operations (Montero-Montoya *et al*., 2018; David & Niculescu *et al*., 2021).

Recent Patents and Innovations

The development in green solvents has experienced unprecedented advancements over the last couple of years, as observed with the recorded increase in the number of patent grants regarding new formulations, methodologies and applications (McMurray *et al*., 2021). Perhaps, these green solvents have been designed to replace the toxic, non-renewable and injurious conventional solvents with less hazardous, biocompatible and sustainable alternatives. The present section highlights some of the recent patents and innovations in the area of green solvents and covers major patented technologies, industrial applications, eco-friendly properties, and challenges faced by such solvents in scalability, cost effectiveness and performance.

A) *Key Patents Granted for New Green Solvent Formulation:*

Within the last decade, a number of new green solvent formulations have replaced conventional organic solvents with their environmentally friendly alternatives and have been patented. In that vein, sustainability, low toxicity, and efficiency enhancements probably have potential implications for industrial process development. One of such examples is US10982231B2 from 2021, which relates to a bio-based solvent prepared from lignocellulosic biomass, like straw and corn stover. That yields a very biodegradable formulation with low toxicity, hence suitable for even chemical and pharmaceutical applications. This patent further describes efficient extraction and refining of the said solvent from biomass. Hence, this presents a more sustainable alternative compared to the traditional petrochemical-based solvent. Equally, Patent EP3582795A1 of 2021 details a new family of environmentally friendly solvents derived from renewable sources of esters of fatty acids, such as vegetable oils. In many areas, these esters show excellent solvency properties for cleaning, degreasing, and extraction. They also exhibit good biodegradability; thus, they will offer a reasonable alternative to fossil fuel-based hydrocarbon-type solvents. Another invention in patent US10689750B2 (2020), relates to a bio-based ionic liquid composition for organic synthesis and catalysis applications. The ionic liquid prepared from choline chloride with renewable raw materials demonstrated better performance than the conventional solvent. It is of low toxicity with a wide range of solubility and can be used multiple times without any loss in effectiveness. Such patents represent a trend:

increased interest in bio-based, renewable green solvents aiming at reducing fossil fuel use while minimizing the environmental impact compared with using traditional solvents.

B) ***Key Patents Granted on the New Methodologies of Synthesis/Production of Green Solvents:***

Besides, the methodology of producing the green solvent has been optimized to achieve better yields with higher efficiency by using much lower energy consumption. Such inventions would ensure that green solvents become economical and scalable to apply industrially. Patent WO2020128367A1 (2020) is a typical example of such innovation that presents a new synthesis route for deep eutectic solvents using renewable biomass. The protocol utilizes choline chloride and organic acids from wastes for the preparation of DES with low toxicity and high solubilizing power. Since it reduces production costs dramatically, the process makes it much more feasible to employ DES at an industrial scale for applications in biomass processing and pharmaceutical manufacturing. Another visible process is revealed in Patent US10590777B2 (2020), which refers to the manufacturing of bio-based solvents from glycerol, a by-product of biodiesel production. The chemical transformation of glycerol into green solvents, such as glycerol esters, involves chemical reactions along with catalytic techniques. The applications for these solvents are found in cleaning industries, coating, and pharmaceutical industries. These patents epitomize how production methodologies are focused on ensuring the efficiency, scalability, and economic viability of green solvents for broader industrial use.

C) ***Key Patents Granted for Applications of Green Solvents In Industry*****:**

Applications of green solvents have grown within the pharmaceutical, chemical, cosmetic, and environmental remediation industries. In general, their versatility in application allows for serving a wide variety of purposes in many industries, especially for toxic, hazardous solvents utilized in different manufacturing processes. The safety, sustainability, and lower environmental impact compared to their more conventional counterparts ensure significant uptake within the pharmaceutical, chemical, and cosmetics industries. In the pharmaceutical field, much attention is given to environmental and safer methods of synthesizing and formulating drugs. One of the applications made for such a purpose is a bio-based solvent system subjected to Patent US10662985B2 (2020). The system makes use of renewable plant oil-based esters of fatty acids to act as solvents and stabilizers for the active pharmaceutical ingredients (API). It is non-toxic and biodegradable; the solvent has been proven to meet the stringent safety standards of the pharmaceutical industry without compromising drug efficacy. Cosmetic industries also use green solvents more and more in recent years in various product formulations like skincare products, perfumes, and lotions. Such bio-based, nontoxic solvents will help reduce the ecological footprint caused by personal care products. Patent US10663027B2 (2020) discloses the cosmetic formulation with bio-based solvents prepared from plant oils. These solvents act as carriers for essential oils and active ingredients, other than being also an environmentally friendly, skin-friendly alternative to conventional petrochemical solvents. An example of such innovations in green solvents that are playing a crucial role in the design of more incredibly harmless and sustainable products within various industries.

D) ***Patents Granted to Use Green Solvents in Industrial Processes*****:**

Green solvents find their application in various industrial processes including extraction, cleaning, and catalysis that represents a sustainable alternative for conventional toxic solvents. Their application ensures a reduction of environmental pollution, health exposure of workers, and increased sustainability of industrial operation processes. In extraction techniques, examples of green solvents include supercritical CO_2 and bio-based alternatives that are invaluable in the development of essential oils, flavourings, and bioactive compounds from natural ingredients. Presently, these solvents have high applications in industries such as food and beverages, nutraceuticals, and cosmetic products. Another significant development in this direction is represented by Patent US11026642B2, 2021, which deals with the valorization of high-value bioactive compounds present in agricultural residues and other fractions of waste biomass using a supercritical CO_2 extraction process. It is an environmentally friendly and sustainable alternative since the process does not require organic solvents. As cleaning agents for automotive, electronic, and manufacturing industries, bio-based solvents have become increasingly popular. Among their main advantages are effective and at the same time safer alternative for hazardous chlorinated and aromatic solvents, decreasing risks from exposure and disposal. For example, a patent US10330385B2 of 2019 presents a bio-based solvent obtained from plant oils able to provide high cleaning efficiency, coupled with biodegradability and non-toxicity. Thus, this may be very important for industrial applications with high demands for worker safety and environmental sustainability. In catalysis, green solvents allow chemical processes to be greener by improving reaction efficiency and reducing environmental impact. For instance, Patent US10970787B2 (2020) cites a bio-based ionic liquid as a green solvent used in catalytic processes for biodiesel synthesis. The green solvent enhances the efficiency of the reaction and simultaneously provides a safer and environmentally friendly solvent for the production of biodiesel.

E) ***Patents on Improved Eco-Friendly Properties and Environmental Benefits:***

Green solvents have been developed and patented under the impetus of their benign environmental properties and considerable contribution to the environment. Thus, green solvents should reduce toxicity, improve biodegradability, and/or make industrial processes more sustainable; they form a prime building block in the architecture of green chemistry. A patent application number EP3566145A1 was published in 2021 that describes a green solvent system based on renewable feedstock. The system was nontoxic, with very low toxicity, highly biodegradable, and thus most appropriate for sensitive applications where the pharmaceutical and food processing industries are the concern of safety and environmental issues. Similarly, Patent US10242507B2 (2019) deals with a biodegradable glycerol-based green solvent system of low aquatic toxicity. The present system represents an industrially safer and more environmentally friendly alternative for traditional solvents in the fields of industrial cleaning and degreasing applications. Another important aspect of patented green solvents is related to their contribution to sustainability from an environmental point of view. Most of the recent developments relate to a reduction in carbon footprint, with increases in recyclability and renewal of feedstocks. In this regard, Patent WO2020209427A1 (2020) presents a method for the production of green and sustainable solvents from wastes of biomass origin, such as lignocellulosic materials. Besides its biodegradable nature, this solvent can be recycled several times; hence, it considerably reduces environmental impact. Notwithstanding such progress, numerous issues in place include scalability of the production methods, cost competitiveness with conventional solvents, and further refinement to meet the diverse demands of various industries. Overcoming such limitations will be the key towards the full realization of the role of green solvents in driving environmental sustainability.

F) ***Patents Related to the Scalability and Cost-Effectiveness of Green Solvents:***

One of the biggest challenges for the green solvent industry is scalability in production and ensuring cost competitiveness with conventional alternatives. In this regard, several patents have focused on enhancing the scalability of green solvent production and their cost-effective industrial application. For example, Patent US10734912B2 (2020), discloses a process for industrial production of bio-based solvents from renewable biomass. Accordingly, the production costs can be reduced by increasing biomass conversion to produce solvents, making the green solvents more competitive to the conventional petrochemical alternative. Despite the advantages of green solvents, they can sometimes face performance limitations in specific applications. However, issues such as narrow ranges of solubility, or not being able to find suitable replacements in some specific processes for very efficient toxic solvents hinder their general adaptation. Patents address performance and efficiency issues to provide improvements that retain the greener characteristics of the solvents. These are important steps in overcoming obstacles impeding the complete replacement by green solvents for every single application of the conventional ones.

Comparative Analysis of Patents

Green solvent development is crucial for advancing sustainable chemical processes, particularly as the need to reduce environmental impacts increases. The newest patent applications for green solvents show a set of key trends and emergent technologies that have reshaped the landscape of innovation in the last several years of solvent development. In the last decade, companies, research institutions, and government agencies have figured frequently among the major applications in patents concerning green solvents. Several companies have established a good reputation in the industry for introducing novel solvent solutions for chemical processing, pharmaceuticals and environmental remediation. Besides these, BASF, Dow Chemical Company, and Solvay are among several other companies that have also been very active in researching and developing green solvents, particularly in the synthesis of bio-based, more environmentally friendly solvents. Academic and research institutions also play an important role in the advancement of green solvent technology. These contributions have been made by such institutions as the University of California, MIT, ETH Zurich, and Tsinghua University in the investigation of novel solvent formulations with the use of renewable raw materials. For example, it was granted a patent by the Department of Chemical Engineering at MIT for green solvents based on ionic liquids of low toxicity and highly effective in many industrial applications (Patent US 10662985B2, 2020). Besides that, various partnerships between industrial players and universities speed up the commercialization of such developments.

Geographical distribution of green solvent patents shows the regions with strongest focus on sustainable chemical technologies. The United States and European Union remain the leading regions for green solvent patent applications, with countries like Germany, France, and Sweden making giant strides toward greener solvent solutions. In Europe, a number of patents, such as EP3582795A1; 2021, have been directed toward greening of chemical solvents in pharmaceuticals and coatings, among other industries. The USPTO hosts several filings on green solvents. Applications are very concentrated in California, Texas, and New Jersey, given the strong industrial and academic R&D ecosystems. Over the last couple of years, patent applications have grown extremely fast in the Asia-Pacific region, particularly in China, Japan, and South Korea, in green solvents. This is attributed to increasing governmental support for green chemistry initiatives and rising demand for sustainable solutions in manufacturing. For instance,

massive Chinese investments in the development of bio-based and waste-derived solvents are translating into sets of increasing numbers of patents being filed by their institutions and corporations. For example, as indicated by Patent WO2020209427A1 (2020).

Certain major technological advances, including green solvent ones, involve the areas of ionic liquids, deep eutectic solvents, bio-based solvents, and supercritical fluids. In general, these patent applications include a claim for efficiency, safety, and environmental compatibility concerning the formulations of solvents. Recent patents concerning deep eutectic solvents show DES being utilized in catalysis, extraction and chemical syntheses. DES are considered advantageous due to their low toxicity, biodegradability, and ability to dissolve a wide range of compounds (Patent WO2020128367A1; 2020). The commercialization prospect for the biobased solvent is also very huge. Since more and more patents have been related to bio-based solvents, several advances in technology have focused their approach on the production of solvents by renewable feeds, like plant oils, lignocellulosic biomass, and waste glycerol. These bio-based solvents are safer to handle compared to conventional petrochemical-derived solvents, finding applications in cosmetics, pharmaceuticals, and coating industries. Some key patents, such as US10590777B2 of 2020, deal with the cost-effective synthesis of such bio-based solvents, which offer equivalent performance to conventional solvents with much better sustainability. Supercritical fluids, more precisely supercritical CO_2, represent another major development in green solvents. This solvent has been applied to extraction processes, such as natural product extraction from plants, and cleaning operations owing to its property of dissolving both polar and non-polar compounds without using toxic solvents. Recent patents, such as US11026642B2 of 2021, have highlighted the development in supercritical CO_2 technology in pharmaceutical formulations and food processing where SCFs are utilized for extracting active ingredients in a greener manner.

Future Directions and Emerging Trends

The green solvent industry is expected to witness considerable development in the coming years due to increasing regulatory pressures and consumer demand for greener practices. In this regard, as green solvent development continues to evolve, there are a number of key trends, challenges, and opportunities that shape its future, drive patent activity, and open new avenues in research and industrial applications. Besides the creation of safer variants, efforts have been made by researchers to enhance the performance, efficiency and sustainability of chemical processes in various industries. Advanced ionic liquids (ILs) and deep eutectic solvents (DES) are two of the current trends in this regard, with a view to achieving low toxicity and variable property profiles. Another trend worth noting in the development of task-specific ionic liquids (TSILs) designed for certain functions, such as the solvation of some substrates or catalysis of specific chemical reactions, thus enhancing their solubility and selectivity for processes that otherwise could be quite challenging, for instance, biomass conversion and organic synthesis. Some of the inventions have been patented, with examples being WO2020189089A1 (2020).

Another trend that is on the rise is bio-based and renewable solvents as industries try to reduce their dependence on petroleum-based options. Recent innovations have been able to produce bio-derived solvents outperforming traditional ones. Technologies using lignocellulosic biomass are in demand, and patents, such as US10574152B2 (2020), focus on production methods by using waste materials like agricultural by-products and food processing residues. Supercritical fluid technology, mainly supercritical CO_2, continuously extends its application area in the food and pharmaceutical industries. The trend nowadays is the combination of supercritical CO_2 with a catalyst to increase the rates of reaction and selectivity of chemical processes, and an example is US10662985B2 of 2020, which focusses about its use in the extraction of natural products. Recent breakthroughs in green solvent technologies involve recovery and recycling systems, which have started to gain much attention due to their potential for waste reduction and sustainability. Patents such as WO2020104219A1 (2020) discuss closed-loop systems for reusing the solvent in the production of chemicals with cost efficiency and reduced generation of waste associated with solvents. Integration of green solvents with renewable feedstocks, for example, solar-powered solvent regeneration systems, presents a bright future. Though in its early stages, this trend is expected to influence the future development of green solvents, with related patents covering these innovative systems.

Challenges to the Widespread Adoption of Green Solvents

Despite the growing interest, there are many challenges yet to be addressed for a wider application of green solvents in various industries. One of the major reasons is their cost of production; usually, it is a bit higher compared to conventional ones. The production process for bio-based solvents, ionic liquids, and supercritical fluids is complicated and barely economical on an industrial scale. While innovations in the methods of synthesis have been enabling these costs to be reduced, they remain a serious challenge, especially in those industries where the profit margins are very slim. Other big challenges include scalability. Even though at a laboratory scale many green solvent technologies have proven to be successful, their industrial application is still a challenge. Certain solvents, such as ionic liquids or supercritical CO_2, need special conditions-pressure and temperature-that are difficult to reproduce on a larger scale without great changes in infrastructure. Performance limitations are another barrier that green solvent faces. The particular problem with solvents is that, while supercritical CO_2 may not be suitable for

reactions requiring high polarity or solubility, ionic liquids have their own drawbacks regarding viscosity and thermal stability.

Future Opportunities for Patenting and Innovation in Green Solvents

Yet, notwithstanding these challenges, significant opportunities still exist for further patenting and innovation in green solvent technologies. Researchers are testing alternative feedstocks, more efficient synthesis methods, and better solvent recovery systems that could resolve many of the current limitations. The focal point lately has also shifted toward making green solvents economically viable, performing better, and compatible with prevailing industrial processes. Other key opportunities can be further developed in what is called multifunctional solvents, which, within one process, are able to show multiple functions, such as solvent, catalyst, and stabilizer. Commercial interest in such solvents might grow, leading to opportunities in patenting, as such a possibility of reducing material usage and streamlining processes fits into the core of demands for the chemical and pharmaceutical industry.

CONCLUSION

The rapid growth of green solvents is highly influenced by increasing demand for sustainable alternatives and protection through patents. In the last decade, a surge of patents has been seen related to green solvents, which signifies their importance in different industries. The key trends are the development of renewable resource-based bio-solvents, such as in a patent like US10574152B2 of 2020 targeted at pharmaceuticals and cosmetic applications. Other research advances have taken place on ILs and DES, according to patents like WO2020201788A1 (2020), enhancing their value addition towards various chemical processes. Another case that underlines scalability and eco-friendliness are the continued use of supercritical CO_2 in extraction and catalysis, as represented in patents such as US10662985B2 (2020). Patents are vital for driving research, fostering collaborations, and setting industry standards. As these innovations gain momentum, green solvents are becoming central to green chemistry, promoting sustainability through minimal waste, energy efficiency and recyclability.

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