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Green Analytical Approaches and Eco-friendly Solvents: Advancing Industrial Applications and Environmental Sustainability: A Comprehensive Review

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ABSTRACT

The shift towards environmental sustainability in industrial processes has intensified the demand for eco-friendly solvents, as traditional organic solvents pose significant ecological and health risks due to their volatility, toxicity, and environmental persistence. Green solvents derived from renewable resources or designed to minimize environmental impact, provide a sustainable solution and are gaining traction as viable substitutes in industries such as pharmaceuticals, agriculture, and materials manufacturing. This review explores advancements in the use of green solvents like water, ionic liquids, supercritical fluids, bio-based solvents, and deep eutectic solvents. These alternatives are valued for properties such as non-volatility, low toxicity, biodegradability, and recyclability, which reduce the environmental footprint of industrial operations. For instance, supercritical carbon dioxide ($scCO_2$) has proven versatile in decaffeination and pharmaceutical synthesis, while ionic liquids are favoured for electrochemical and separation processes due to their tunable properties. Bio-based solvents, like ethyl lactate from renewable biomass, exemplify the integration of circular economy principles. Despite their benefits, challenges such as scalability, production costs, and the need for thorough life-cycle assessments remain. Continued research, industry collaboration, and regulatory support are essential to overcome these hurdles and accelerate the adoption of green solvent technologies. By embracing these eco-friendly alternatives, industries can significantly reduce pollution, conserve resources, and achieve global sustainability goals, contributing to a cleaner, healthier, and more sustainable future.

Keywords: Green solvents, Environmental footprint, Eco-friendly, Bio-based solvents and Industrial processes.

INTRODUCTION

As the urgency for environmental sustainability escalates, industries are increasingly turning to eco-friendly solvents as a safer and more responsible alternative to traditional organic options. The growing awareness of environmental sustainability has intensified the demand for greener alternatives in industrial processes, including eco-friendly solvents[1]. Traditional organic solvents, used widely in industries like pharmaceuticals, agriculture, and materials manufacturing, pose significant ecological and health risks due to their volatility, toxicity, and persistence in the environment. Green solvents derived from renewable resources or designed to have minimal environmental impact, offer a sustainable solution to mitigate these challenges and have gained traction as viable substitutes[2]. These solvents not only reduce the harmful effects associated with conventional options but also align with the increasing regulatory pressures aimed at minimizing environmental footprints. Moreover, green solvents can enhance the efficiency of industrial processes by providing comparable or even superior performance characteristics to their traditional counterparts. For instance, bio-based solvents such as ethyl lactate and glycerol are not only biodegradable but also exhibit excellent solvency power for a range of applications, from cleaning agents to reaction media in chemical synthesis[3]. The transition towards these eco-friendly alternatives is further supported by advancements in research and development that focus on improving their performance metrics while reducing costs. As industries strive to meet sustainability goals, adopting green solvents can lead to significant reductions in emissions and waste generation, ultimately contributing to a more circular economy. Incorporating green solvents into industrial practices is not merely an ethical choice; it is an economically sound strategy that can enhance brand reputation and appeal to increasingly eco-conscious consumers[4]. By making this shift now, companies position themselves favourably within a competitive market landscape that values innovation and responsibility toward our planet's future[5].

Solvents play a crucial role in determining the environmental performance of chemical industry processes and significantly influence cost, safety, and health considerations. The concept of "green" solvents aims to reduce the environmental impact associated with solvent use in chemical production. This raises the question of how to evaluate the environmental friendliness of a solvent. A comprehensive framework is proposed for assessing solvents environmental performance, encompassing key aspects such as substance-specific hazards, emissions, and resource usage throughout the solvent's entire life cycle. The framework is applied to 26 organic solvents, revealing that simple alcohols and alkanes are more environmentally favourable, whereas solvents such as dioxane, acetonitrile, acids, formaldehyde, and tetrahydrofuran are less sustainable. A case study involving alcohol–water and pure alcohol mixtures for the solvolysis of p-methoxybenzoyl chloride demonstrates that methanol–water or ethanol-water mixtures are more environmentally advantageous than pure alcohol or propanol-water mixtures. These examples highlight the framework's utility in identifying environmentally sound solvents and mixtures for chemical industry applications. Additionally, the framework can facilitate the assessment of emerging solvent technologies, provided the current data limitations are addressed[6-7].

This review highlights a critical call to action for industries to prioritize green solvents, emphasizing that continued research, collaborative efforts, and robust regulatory support are essential for accelerating their adoption across various sectors. By investing in eco-friendly solvent technologies, companies not only enhance their operational efficiency but also play a vital role in the larger mission of reducing pollution and conserving precious resources. The transition to these sustainable alternatives presents an opportunity for industries to align with global sustainability goals, demonstrating their commitment to environmental stewardship while also meeting consumer demand for greener products. Furthermore, industry collaboration can drive innovation and share best practices, creating a ripple effect that encourages more businesses to adopt these technologies. As we move towards a cleaner and healthier planet, it is imperative that stakeholders recognize the immense potential of green solvents in fostering sustainability. Embracing this shift today will undoubtedly pave the way for a brighter future for generations yet to come.

Green solvents and their applications

Green solvents are eco-friendly alternatives to conventional solvents, designed to reduce environmental and health impacts while maintaining efficiency in chemical processes. Examples of green solvents include ionic liquids, supercritical carbon dioxide, and deep eutectic solvents (DESs) and etc. These solvents are gaining attention for their versatility, recyclability, and low toxicity, making them suitable for applications such as biomass conversion, catalysis, and material synthesis. Green solvents are being widely applied across several industrial fields due to their eco-friendly and sustainable properties[8-9]. Applications of green solvents are given in Figure 1.

Pharmaceuticals: Green solvents used in drug synthesis, formulation, and extraction to reduce toxicity and improve safety.

Agrochemicals: These are employed in the production of bio-pesticides and herbicides to reduce environmental hazards.

Biomass Conversion: These solvents are utilized in the conversion of biomass to biofuels or valuable chemicals, enhancing process efficiency.

Electronics: Serve as solvents in the production of semiconductors and electronics due to their non-toxicity and recyclability.

Catalysis and Extraction: Applied in green catalysis and separation processes, including solvent extraction and purification.

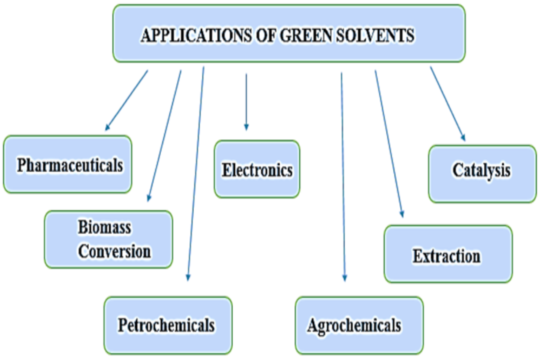

Fig. 1. Applications of green solvents

Types of green solvents

Water

Universally available and non-toxic, water is an excellent solvent for many industrial processes, including extractions and reactions. Techniques like aqueous biphasic systems enhance its utility in green chemistry applications.

Supercritical Fluids

Supercritical Carbon Dioxide ($scCO_2$): A widely used green solvent, $scCO_2$ is effective in decaffeination, extraction, and cleaning processes due to its non-toxicity, recyclability, and mild operating conditions.

Ionic Liquids

Composed of organic cations and inorganic anions, ionic liquids have negligible volatility, tunable properties, and are used in catalysis, separations, and electrochemical processes.

Deep Eutectic Solvents (DES)

Formed by mixing two or more components that interact to lower the melting point, DES are biodegradable, low-cost, and used in metal extraction, synthesis, and bio-refining.

Bio-Based Solvents

Derived from renewable sources such as plants, examples include:

Ethyl Lactate: Derived from lactic acid, used in cleaning and coatings.

d-Limonene: Extracted from citrus fruits, applied in degreasing and cleaning.

Alcohols and Glycerol

Renewable alcohols (e.g., ethanol) and glycerol (A by-products of biodiesel production) serve as sustainable alternatives in reactions and formulations.

Organic Carbonates

Examples like dimethyl carbonate (DMC) are non-toxic and biodegradable, used in polycarbonate production and as solvents for organic synthesis.

Fluorous Solvents

Highly selective solvents with low environmental impact, applied in organic synthesis and separations[10-11].

Benefits of green solvents

Environmental Benefits

Reduced Toxicity: Green solvents are designed to have low environmental and human toxicity, minimizing harmful emissions and waste.

Biodegradability: Many green solvents break down naturally, reducing persistence in the environment.

Low Volatility: They reduce air pollution by limiting volatile organic compound (VOC) emissions.

Economic Advantages

Resource Efficiency: Green solvents, such as supercritical CO_2 and water, are recyclable, reducing raw material consumption and waste treatment costs.

Cost Savings: While initial production costs may be higher, lower disposal costs and improved process efficiencies provide long-term economic benefits.

Improved Safety

Non-Flammability: Many green solvents are non-flammable, enhancing workplace safety.

Reduced Exposure Risks: Safer handling properties protect workers from hazardous solvent exposure.

Process Enhancements

Higher Selectivity and Efficiency: Green solvents like ionic liquids and supercritical fluids can improve reaction selectivity and product yields.

Customizability: Solvents such as ionic liquids and deep eutectic solvents can be tailored for specific applications.

Sustainability

Renewable Sources: Bio-based solvents, derived from renewable materials, support a circular economy[10-11].

Alignment with Green Chemistry Principles: Using green solvents helps industries comply with regulatory standards and adopt sustainable practices.

Importance of green solvents in reducing environmental footprints

Green solvents are eco-friendly alternatives to traditional toxic and non-biodegradable solvents, addressing sustainability concerns in industrial processes. Their low toxicity, biodegradability, and recyclability minimize pollution, conserve resources, and reduce greenhouse gas emissions. Used in pharmaceuticals and materials manufacturing, they support sustainable practices, aligning industries with global environmental goals. Examples like ionic liquids and deep eutectic solvents offer tunable properties for efficiency across applications. Despite challenges in cost and scalability, advances in green chemistry enable cleaner, energy-efficient processes, helping industries reduce their environmental impact and promote a healthier planet[12-13]. Benefits and importance of green solvents are given in Figure 2.

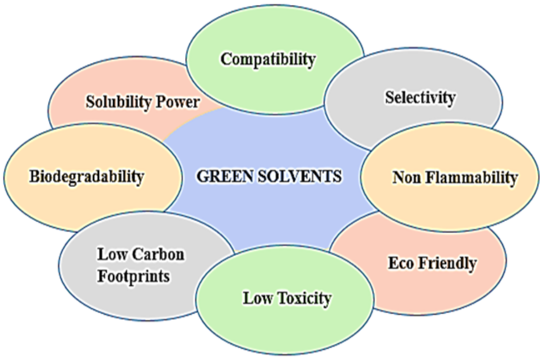

Fig. 2. Benefits and importance of green solvents

Adoption of green solvents for industrial applications

Green solvents are transforming industries by reducing environmental impact and enhancing sustainability. Bio-based solvents, ionic liquids, and deep eutectic solvents offer renewable, low-toxicity alternatives to volatile organic compounds (VOCs), reducing energy consumption and harmful emissions. Widely used in pharmaceuticals, agrochemicals, and materials science, they replace toxic solvents in synthesis and extraction processes. Integrating green solvents with green chemistry principles, such as catalysis and waste minimization, amplifies their benefits. While challenges like cost and scalability remain, advancements in research, policy incentives, and growing sustainability awareness are driving their adoption, making green solvents pivotal for eco-friendly industrial practices[14].

Scalability and Commercial Viability: While green solvents demonstrate significant environmental benefits, their application at an industrial scale remains challenging. There is a lack of detailed studies and frameworks addressing the economic feasibility, supply chain logistics, and scalability of green solvent production and utilization in various industries.

Life-Cycle Assessments: Comprehensive LCAs for green solvents are limited, particularly in comparing their environmental footprints with conventional solvents over their entire lifecycle. Existing research often focuses on specific phases (e.g., production or disposal), leaving gaps in understanding their true sustainability.

Economic Analysis of Production Costs: Green solvents, often involve high initial production costs. Research on cost-reduction strategies, such as process optimization, use of abundant raw materials, or waste valorization, is still inadequate.

Performance Optimization: Although many green solvents show promise, their performance under diverse industrial conditions (e.g., Extreme temperatures or pressures) requires further investigation. Understanding their physicochemical stability, efficiency, and compatibility in various applications remains a key research need.

Regulatory and Policy Frameworks: Limited studies explore the influence of regulatory policies and incentives on the adoption of green solvents. Research is needed to identify policy gaps and propose mechanisms to encourage industries to transition from conventional to green solvents.

Toxicity and Long-Term Impacts: While green solvents are designed to be less toxic, their long-term effects on ecosystems, human health, and material compatibility remain underexplored. There is a need for standardized toxicity testing and environmental impact assessments.

Integration with Circular Economy Principles: Although bio-based solvents like ethyl lactate align with circular economy goals, the potential for integrating green solvent technologies into broader circular economy frameworks is not well-studied. Research can focus on closed-loop systems for solvent recovery and reuse.

Limited Applications in Emerging Industries: Most studies focus on traditional industries (e.g., Pharmaceuticals, agriculture). Research exploring green solvent applications in emerging fields like nanotechnology, renewable energy, and advanced manufacturing remains sparse.

Consumer Perception and Market Demand: Understanding consumer and industry attitudes toward green solvents is critical for driving adoption. There is limited research on awareness, acceptance, and perceived barriers among stakeholders.

Collaboration and Knowledge Sharing: The absence of collaborative platforms between academia, industry, and policymakers hinders the development of innovative green solvent solutions. Research on fostering multi-sectoral collaboration and knowledge exchange can accelerate progress. The above needs could significantly enhance the adoption and effectiveness of green solvents, enabling industries to achieve sustainability targets and minimize their environmental footprint.

Advancements in green solvents for industrial applications

Green solvents are gaining widespread adoption as industries prioritize sustainability and environmental responsibility. Unlike traditional solvents, which generate harmful emissions and waste, green solvents are derived from renewable resources and offer low toxicity. Industries such as pharmaceuticals and coatings benefit from these eco-friendly alternatives, which reduce waste disposal costs and ensure regulatory compliance. Advances in green solvent technology, including bio-based formulations, enhance efficiency without compromising performance. Beyond operational benefits, adopting green solvents improves brand reputation, attracting environmentally conscious consumers and fostering market competitiveness. Embracing green solvents supports sustainability efforts while driving economic growth through responsible resource management[2,10,15-17].

Advancements in green solvents are as follows:

Water as a Green Solvent

Water is used widely due to its harmless, abundant, and versatile nature for reactions like hydrolysis and extraction processes. Furthermore, its role as a solvent is unparalleled; many substances dissolve in water, making it essential for countless chemical reactions. Water's unique properties also allow it to facilitate temperature regulation in industrial processes, a crucial factor for maintaining optimal conditions. In agricultural practices, water supports irrigation systems that are vital for crop growth and food production. The agricultural sector relies heavily on effective water management to ensure that crops receive adequate hydration without wastage. Moreover, in the realm of energy production, water is utilized in hydropower plants and thermal power stations, demonstrating its importance beyond just chemical applications. Given these diverse uses, the efficient management and conservation of water resources are imperative. As global populations rise and industrial demands increase, ensuring sustainable access to clean water will not only benefit economic growth but also safeguard our environment for future generations. Investing in technologies that enhance water purification and recycling can further bolster our ability to harness this invaluable resource effectively while mitigating potential shortages.

Ionic Liquids

These solvents are non-volatile and highly tunable, enabling their use in CO_2 conversion and material frameworks like metal-organic frameworks. They show promise in minimizing waste and energy usage during chemical reactions[18-19]. These Liquids are customizable solvents which are employed in catalysis and CO_2 capture, minimizing environmental hazards. Their unique properties, such as low vapour pressure and thermal stability, make them ideal candidates for green chemistry applications. By adjusting the composition of ionic liquids, researchers can tailor their solubility and reactivity to suit specific processes, leading to optimized outcomes in various chemical reactions. Moreover, ionic liquids can facilitate the separation and recovery of valuable products while reducing waste generation. This attribute is particularly advantageous in industrial settings where resource conservation is paramount. With ongoing advancements in ionic liquid technology, including their use in electrochemistry and energy storage systems, the potential for these solvents to revolutionize traditional methods is immense. Incorporating ionic liquids into standard practices not only aligns with sustainable development goals but also paves the way for innovative approaches that could reshape entire industries. As we continue to face mounting environmental challenges, embracing such versatile solutions becomes not just beneficial but essential for a greener future.

Supercritical Fluids (e.g., $scCO_2$)

This is a non-toxic, recyclable solvent used in processes like extractions and polymerization. Its environmentally benign nature makes it an excellent choice for green chemistry[20]. These are applied in decaffeination and polymerization, offering recyclability and low toxicity. Because of their special qualities, supercritical fluids-like supercritical carbon dioxide ($scCO_2$) have become highly effective solvents in industrial operations. Their capacity to selectively dissolve caffeine provides high-quality, chemical-free products, which is why they are widely utilised in applications like decaffeinating coffee and tea. The $scCO_2$ is an effective medium for polymerisation that produces environmentally acceptable polymers without using dangerous organic solvents. Its low toxicity and recyclability minimise negative effects on the environment and human health, making it an essential part of sustainable industrial chemistry.

Bio-Based Solvents

Bio based solvents derived from renewable sources, they are prominent in pharmaceutical and agrochemical industries. Bio-based solvents have become more popular in sectors looking to lessen their dependency on fossil fuels because they are made from sustainable raw materials such plant oils, sugars, and agricultural waste. These solvents offer safer substitutes for drug formulation and synthesis in the pharmaceutical industry, guaranteeing less hazardous residues and improved patient safety. They make it easier to produce pesticides and herbicides with less of an adverse effect on the environment in agrochemicals. Bio-based solvents are crucial for sustainable industrial practices because of their biodegradability and compatibility with green chemistry concepts, which connect environmental responsibility with functional efficiency.

Deep Eutectic Solvents (DESs)

These are low-cost, biodegradable alternatives used in biodiesel production and upgrading biomass into valuable chemicals like 5-hydroxymethylfurfural. Their adaptability and potential for recycling make DESs particularly attractive in sustainable chemical practices[18-20]. DESs are ideal for biomass conversion and metal recovery. A type of cutting-edge green solvents known for their remarkable non-toxicity and biodegradability are deep eutectic solvents (DESs). These solvents have customisable physicochemical features because they are created by combining donors and acceptors of hydrogen bonds. DESs are especially well-suited for biomass conversion, as they effectively convert lignocellulosic material into useful fuels and chemicals. By dissolving and separating metals from electronic trash or ores, they also play a critical role in metal recovery. DESs are an essential tool for sustainable industrial applications because of their affordability and environmental friendliness. In biodiesel production, DESs have been effectively used to process fatty acids and polysaccharides, achieving high efficiency with minimal environmental impact. Additionally, they facilitate recycling and reusability, making them cost-effective. Green solvents have also been applied in the purification of fullerenes (C60), significantly reducing chemical hazards and environmental costs compared to traditional methods.

Sustainability in Solvent Use

Advancements in green solvents demonstrated potential for reducing industrial pollution while maintaining efficiency. Research highlighted second-generation solvents, like ionic liquids and liquid polymers, as promising solutions for sustainable industrial applications. However, challenges such as cost, scalability, and limited understanding of long-term environmental impacts were identified, emphasizing the importance of continued research and regulatory support[21].

Economic and Environmental Synergy

The adoption of green solvents is increasingly cost-competitive due to advancements in scalable production methods, aligning environmental goals with economic viability. Green solvent usage is become more affordable as scalable production techniques reduce manufacturing costs while preserving environmental advantages. Industries can incorporate green solvents into operations without incurring large costs by coordinating financial incentives with environmental objectives. The shift to environmentally friendly industrial processes is fuelled by the broad adoption across industries that are encouraged by this balance between affordability and sustainability. The adoption of water-based and bio-derived solvents highlights their ability to reduce waste and energy consumption in industrial applications. However, the lack of uniform regulations and high initial costs are key barriers that need addressing to accelerate widespread adoption[22].

Hybrid Systems

Combining green solvents like ionic liquids with traditional solvents enhances process efficiency while reducing environmental impact. In industrial operations, there are several benefits to combining conventional solvents with green solvents, such as ionic liquids. By utilising the special qualities of ionic liquids, such as their tunability and non-volatility, this hybrid technique enables increased efficiency while preserving the practical advantages and familiarity with traditional solvents. These combinations can lower energy usage, increase selectivity, and maximise reaction rates. By reducing the toxicity and waste linked to conventional solvents, this combination also lessens the total environmental impact and promotes more economical and sustainable procedures.

Nanotechnology Integration

Green solvents are now used as media for nanoparticles synthesis, contributing to advancements in electronics, medicine, and energy storage. As a sustainable substitute for conventional chemical reagents, green solvents have become successful media for the production of nanoparticles. For the production of nanopartcles, these solvents, such as ionic liquids and bio-based alternatives-offer a more secure and environmentally responsible setting. Advances in a variety of fields, including electronics, where nanoparticles improve conductivity and miniaturisation, medicine, where they are used in drug delivery systems, and energy storage, where they boost battery and super capacitor performance and efficiency, have been greatly aided by this invention. Both technological advancement and environmental sustainability are supported by the use of green solvents in these procedures[23-24].

Pharmaceutical Innovations

The use of bio-based solvents ensures safer drug formulations and reduced toxic residues in the final products. By lowering the possibility of hazardous chemical residues remaining in finished goods, the use of bio-based solvents in medicine formulations greatly improves safety. These biodegradable and non-toxic solvents, which are made from renewable resources like plant oils or sugars, reduce pollution in the environment and make pharmaceutical products safer for consumers. Furthermore, by minimising the requirement for hazardous chemicals and the formulation's overall toxicity both of which are critical for long-term health and safety bio-based solvents help to create cleaner manufacturing processes.

Industrial Applications and Challenges

Eco-friendly solvents are increasingly utilized in processes like polymerization and separation techniques. Still, detailed economic analysis and scalability frameworks are required to replace traditional solvents effectively, especially in resource-intensive industries. The use of green solvents, has grown significantly in industrial processes such as synthesis and material production. These solvents reduce the environmental footprint by replacing volatile organic compounds. Despite progress, the need for further innovation in reaction and separation processes persists, alongside the exploration of biomass transformation as a renewable source for fuels and chemicals. The integration of green solvents with catalysis offers additional control over selectivity and activity in reactions. These developments underscore the role of green solvents in driving sustainable and innovative industrial transformations. Also enable improved efficiency, reduced waste, and lower environmental footprints in processes like extractions, separations, and syntheses.

Challenges of using green solvents

High Initial Costs

The production and synthesis of green solvents, such as ionic liquids and deep eutectic solvents often require specialized techniques, leading to higher initial costs compared to traditional solvents.

Scalability Issues

Many green solvents are still in the experimental phase and face challenges in scaling up for industrial applications. Production at larger scales may involve logistical and technical hurdles.

Complex Synthesis

Some green solvents, like certain ionic liquids, involve complex and energy-intensive manufacturing processes, which may partially offset their environmental benefits.

Limited Versatility

Green solvents may not always match the wide range of applications that conventional solvents can fulfil. Specific solvent properties may limit their use in certain industrial processes.

Stability Concerns

Some green solvents, particularly bio-based solvents, may degrade or lose efficiency over time, especially under extreme conditions such as high temperatures or pressures.

Incomplete Life-Cycle Assessments (LCA)

The true environmental impact of some green solvents remains unclear due to insufficient LCA data. Their benefits can be undermined if production or disposal involves significant environmental costs.

Regulatory and Market Barriers

Adoption of green solvents requires industry and regulatory alignment, which may be slow due to a lack of awareness, established infrastructure for traditional solvents, and potential resistance to change.

Material Compatibility

Certain green solvents may react with or degrade specific materials, limiting their compatibility with existing equipment or industrial processes.

Future directions for using green solvents

Green solvents, characterized by their low toxicity, renewability, and reduced environmental impact, are paving the way for more sustainable industrial practices[25-28].

Innovative Solvent Design

Developing new types of green solvents with improved efficiency, lower toxicity, and enhanced tunability will help address specific industrial needs. Computational chemistry and machine learning can play a significant role in designing these advanced solvents.

Integration with Renewable Energy

Coupling green solvents with renewable energy systems (e.g., solar-or wind-powered processes) can further reduce the carbon footprint of industries. Supercritical fluids and ionic liquids can be particularly beneficial in such energy-efficient setups.

Hybrid Solvent Systems

Combining green solvents with other environmentally friendly technologies, such as catalysis or membrane separation, may enhance process efficiency and broaden application areas.

Life-Cycle Assessment and Sustainability Metrics

Future research should focus on comprehensive life-cycle assessments (LCAs) for green solvents to ensure their production, use, and disposal are truly sustainable. This data can help industries make informed decisions about adopting these alternatives.

Cost Reduction Strategies

Streamlining production methods, using abundant raw materials, and recycling solvents will be crucial to reducing the high initial costs of green solvents.

Expanding Applications

Green solvents can be explored in new fields like nanotechnology, advanced materials synthesis, and biotechnology. Their properties can be tailored for high-value applications such as drug delivery and bio-refining.

Policy and Industry Collaboration

Stronger policies and incentives for adopting green chemistry practices can accelerate the transition to green solvents. Collaboration between academia, industries, and regulatory bodies will be essential to overcome adoption barriers.

Biotechnology Integration

Leveraging enzymatic or microbial processes in tandem with green solvents can enable the development of fully bio-based and low-energy industrial processes.

Green analytical assessment by various software tools

Green analytical chemistry emphasizes minimizing environmental impact in analytical procedures by promoting sustainable practices, reducing waste, and utilizing eco-friendly materials. Recent advancements in software tools allow for comprehensive assessments of analytical methods, aiding in the transition to greener methodologies. Tools like AGREE (Analytical Greenness Metric Approach), Eco-Scale, and the National Environmental Methods Index (NEMI) are commonly used to evaluate and quantify the greenness of analytical techniques. These tools provide insights into method efficiency, environmental safety, and sustainability, fostering informed decision-making in research and industry practices[29].

Retrospective comparative studies of these tools have highlighted their distinct evaluation criteria and scopes. AGREE integrates the 12 principles of green analytical chemistry into a graphical representation, allowing for easy visualization of a method's greenness. In contrast, Eco-Scale focuses on penalty points assigned for factors like reagent toxicity, energy consumption, and waste generation. NEMI employs a simpler four-criteria evaluation, emphasizing method accessibility and waste classification. These differing frameworks provide complementary perspectives, enabling researchers to select tools tailored to specific methodological goals[30].

A critical evaluation of these tools reveals their strengths and limitations. For instance, AGREE offers a comprehensive and visually intuitive scoring system but requires detailed input data, which may not always be readily available. Eco-Scale's simplicity and quantitative approach make it user-friendly but may overlook broader sustainability aspects. NEMI is well-suited for regulatory contexts but lacks the granularity to assess advanced techniques. Combining these tools in a retrospective study has proven valuable in identifying opportunities for improving analytical method sustainability while addressing specific research priorities[31].

Integration of software-based green assessment tools has also demonstrated their utility in method development and optimization. For example, researchers can utilize AGREE to identify non-compliant aspects of their methods, such as the use of hazardous solvents or excessive sample sizes. Eco-Scale, with its focus on reagent consumption and waste generation, enables real-time adjustments to reduce environmental burdens. These tools not only promote compliance with regulatory requirements but also encourage the adoption of greener practices in both academic and industrial laboratories[32].

The comparison of green analytical tools also reveals their application across various analytical fields. AGREE and Eco-Scale have been widely applied in chromatographic and spectroscopic method assessments, particularly in pharmaceutical and environmental research. NEMI has found greater use in regulatory assessments due to its straightforward criteria. In a retrospective study, combining the outputs of these tools provided a more holistic understanding of the environmental and practical impact of analytical methods, highlighting their complementary nature and potential for integration[33]. Advancements in computational techniques have enhanced the precision and applicability of green analytical assessments. Recent updates in AGREE, such as incorporating real-time data input and cloud-based platforms, have improved accessibility and usability. Similarly, updates to Eco-Scale now allow for automated penalty point calculations based on pre-defined databases. These innovations reduce the time and expertise required for assessments, making green analytical evaluation more accessible to a broader range of practitioners[34].

Despite their utility, green analytical software tools face challenges, including the lack of standardization in evaluation metrics. For instance, AGREE emphasizes graphical visualization, while Eco-Scale uses numerical penalty points, leading to potential inconsistencies in comparative studies. Additionally, limited databases for environmental and health impacts of newer reagents or materials may constrain the accuracy of these tools. Addressing these challenges through international standardization and the development of robust databases could enhance the effectiveness of green analytical assessments[35-38].

Future prospects

Enhancing the sustainability of green solvents, investigating their application in cutting-edge technologies, and getting over obstacles such a lack of data for novel applications are the main goals of ongoing research. These substitutes are likely to be crucial in reaching carbon neutrality and promoting green chemistry because to advancements in solvent design. The goal of ongoing research on green solvents is to improve their sustainability by examining their possible uses in developing technologies and refining their features. To promote the use of these alternatives, issues like the scarcity of data for new applications must be resolved. These green solvents are positioned to be crucial in reaching carbon neutrality and promoting green chemistry because to advancements in solvent design. Their incorporation into different industrial processes has the potential to significantly advance the development of a more environmentally conscious and sustainable future.

CONCLUSION

In conclusion, the shift towards green solvents represents a pivotal step in achieving sustainability in industrial processes. Industries can drastically cut pollution, waste, and toxicity by using solvents made from renewable resources or made with little effect on the environment. The advantages of green solvents in terms of effectiveness, safety, and environmental preservation are indisputable, even though issues like scalability and upfront expenditures still exist. Overcoming these obstacles and guaranteeing a sustainable, environmentally friendly future require ongoing research, innovation, and industrial cooperation. Adopting green solvents is an essential part of global environmental initiatives, not merely a fad. Green solvent integration can have long-term economic benefits in addition to lessening the environmental impact, especially as businesses transition to more sustainable methods. In addition to enhancing worker safety, the decreased requirement for dangerous chemicals also lowers the expenses of environmental remediation related to conventional solvents. Green solvents will become more and more cost-effective as technology develops and more environmentally friendly production techniques are created. Additionally, in line with international sustainability objectives, green solvents are crucial in enabling adherence to progressively stringent environmental standards, stimulating industry innovation, and eventually promoting a circular economy.

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Conflicts of interests

Authors are not having any Conflicts of interests in the subject matter included in this manuscript.

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