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Exploring the Catalytic Potential of Ionanofluids in Green Chemistry

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Abstract

Ionanofluids, a unique combination of ionic liquids and nanoparticles, have emerged as a promising class of advanced materials with remarkable potential for sustainable chemistry and catalytic processes. The synergy between ionic liquids' tunable physicochemical properties and nanoparticles' catalytic activity has unlocked numerous opportunities for green chemistry, offering environmentally benign alternatives to traditional solvents and catalysts. These hybrid systems exhibit exceptional thermal stability, low volatility, and high ionic conductivity, making them ideal for applications in energy-efficient reactions and renewable processes. In catalysis, ionanofluids have demonstrated enhanced reaction rates, selectivity, and recyclability in both homogeneous and heterogeneous systems. They have found applications across a diverse range of transformations, including organic synthesis, electrocatalysis, photocatalysis, and biocatalysis. By stabilising catalysts and improving their activity, ionanofluids contribute to reducing energy demands and minimising waste, aligning with the principles of green chemistry. Additionally, their ability to stabilise enzymes and facilitate biocatalytic reactions offers immense potential for industrial biotechnology. Despite their advantages, the widespread adoption of ionanofluids is limited by challenges such as the high cost of ionic liquids, toxicity concerns, and the stability of nanoparticles in the ionic liquid matrix. Addressing these issues through the development of cost-effective, biodegradable ionic liquids and robust nanoparticle systems is essential for broader implementation. Looking ahead, the integration of ionanofluids into renewable energy technologies, environmental remediation, and bio-based chemical processes offers an exciting frontier for research and innovation. This review provides a comprehensive overview of the synthesis, properties, and applications of ionanofluids, with an emphasis on their transformative role in sustainable chemistry and catalysis. It also highlights current challenges and proposes future directions for advancing this interdisciplinary field.

Keywords: *Catalysis; Green Chemistry; Ionanofluids; Nanotechnology; Sustainable Chemistry*

Introduction

Ionanofluids, a hybrid material combining ionic liquids (ILs) and nanoparticles (NPs), represent a significant advancement in the field of nanotechnology and green chemistry (Alqahtani, 2024). Ionic liquids, characterised by their low volatility, high thermal stability, and remarkable ionic conductivity, provide an excellent medium for the dispersion and stabilisation of nanoparticles (Pereira, Souza & Moita, 2024). These nanoparticles, which may include metals, metal oxides, or other nanostructures, impart enhanced catalytic activity, thermal properties, and surface functionality to the composite system. The synergistic combination of these components in ionanofluids not only leverages the individual advantages of ILs and NPs but also results in unique physicochemical properties that surpass those of their individual constituents (Das *et al*., 2021). This combination enables ionanofluids to serve as advanced materials for applications ranging from catalysis and energy storage to environmental remediation and biotechnology.

The significance of ionanofluids lies in their alignment with the principles of sustainable chemistry, offering innovative solutions to pressing environmental and economic challenges (Rahman *et al*., 2024). Traditional chemical processes often rely on volatile organic solvents and energy-intensive conditions, resulting in significant environmental impacts. In contrast, ionanofluids serve as green alternatives that reduce energy consumption, minimise waste generation, and enhance reaction efficiency (Behera, Sangwai & Byun., 2025). Their high thermal and chemical stability allows them to operate under extreme conditions, while their tunable properties enable customisation for specific applications. Furthermore, the incorporation of nanoparticles provides additional functionality, such as improved catalytic activity and recyclability. This makes ionanofluids an ideal choice for achieving sustainability in industrial and academic research settings, particularly in catalytic processes where efficiency and selectivity are paramount (Madheswaran *et al*., 2023).

This review aims to provide a comprehensive understanding of the synthesis, properties, and applications of ionanofluids, emphasizing their transformative role in green and catalytic chemistry. By examining the unique attributes of these materials, we will explore their use in processes ranging from organic synthesis and biocatalysis to electrocatalysis and photocatalysis. The ability of ionanofluids to stabilise catalysts, enhance reaction rates, and enable energy-efficient pathways positions them as a critical technology for addressing global challenges such as energy sustainability, environmental remediation, and resource efficiency. Additionally, the review will discuss the current challenges associated with ionanofluids, such as cost, toxicity, and scalability, and propose strategies to overcome these barriers.

The scope of this review encompasses a detailed analysis of the fundamental properties and synthesis techniques of ionanofluids, followed by an exploration of their applications in sustainable chemistry and catalytic processes. Particular attention will be given to their role as solvents and reaction media, as well as their integration into advanced catalytic systems. Furthermore, the review will highlight emerging trends and future directions, including the development of eco-friendly ionic liquids, the design of multi-functional nanoparticle systems, and the application of ionanofluids in renewable energy technologies. By bridging the gap between material science, chemistry, and engineering, this review aims to provide a foundation for future research and innovation in the field of ionanofluids.

Properties and Synthesis of Ionanofluids

Physicochemical Properties

Ionanofluids are characterised by a unique set of physicochemical properties that make them valuable for a variety of applications in catalysis, energy storage, and sustainable chemistry (Das *et al*., 2021). The properties of ionanofluids stem from the synergistic interaction between the ionic liquids (ILs) and the nanoparticles (NPs) suspended within them. Ionic conductivity, thermal stability, viscosity, and nanostructuring are key attributes that govern their performance in different processes (Figure 1).

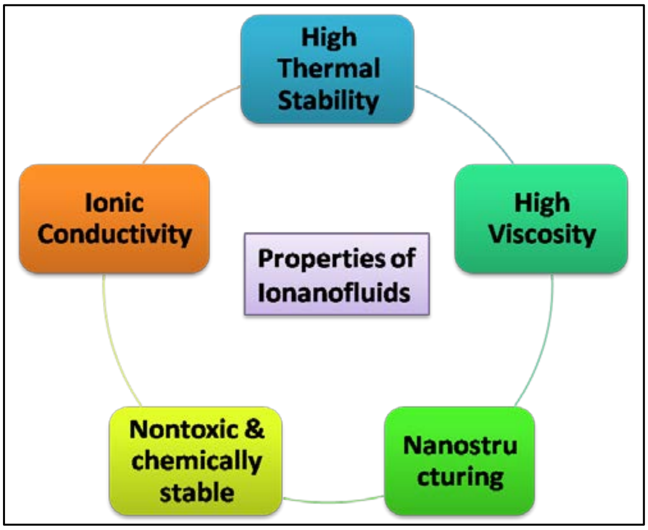

Figure 1: Represents the Various Properties of Ionanofluids

Ionic Conductivity: One of the most significant characteristics of ionanofluids is their high ionic conductivity, which is mainly attributed to the presence of ionic liquids (Joseph *et al*., 2022). Ionic liquids, being composed entirely of ions, exhibit high ionic conductivity, which is advantageous in various electrochemical applications, including fuel cells and energy storage devices. When nanoparticles are incorporated into ionic liquids, the interaction between the IL and the NPs can affect the overall conductivity of the system. For instance, well-dispersed nanoparticles may enhance conductivity by facilitating ionic movement, while agglomeration of nanoparticles can hinder the flow of ions and decrease conductivity (Li, Mbonu & Akcora, 2025).

Thermal Stability: Ionic liquids are known for their exceptional thermal stability, typically operating in temperature ranges between -50°C to over 300°C without decomposing or evaporating (Wang *et al*., 2024). This property makes them ideal for high-temperature catalytic reactions and other industrial processes where conventional solvents would fail. The nanoparticles in ionanofluids can further enhance thermal conductivity, enabling better heat transfer and temperature management in processes that require precise control over temperature (Moulefera *et al.,* 2025). The overall thermal stability of ionanofluids is thus largely determined by the combination of the IL's inherent properties and the type and concentration of nanoparticles used.

Viscosity*:* The viscosity of ionanofluids plays a crucial role in determining their efficiency in various applications, particularly in catalytic processes and energy transfer (Moosavi, Torkzadeh & Akbarinezhad, 2024). While ionic liquids are generally more viscous than conventional organic solvents or water, the addition of nanoparticles can either increase or decrease the viscosity of the system depending on the size, concentration, and dispersion of the particles (Chen, Qiao & Liu, 2022). High viscosity can reduce the diffusion of reactants and hinder reaction rates, but it can also be advantageous in specific applications where stable and thick media are required, such as in lubrication or as heat transfer fluids.

Nanostructuring*:* The presence of nanoparticles in ionic liquids leads to the formation of nanostructured systems that exhibit unique behaviours not seen in pure ILs or conventional nanofluids (Bo *et al*., 2022). These nanostructures, which can range from well-dispersed nanoparticles to aggregated clusters, can significantly alter the physical and chemical properties of the fluid. The interaction between the IL and the nanoparticle surface can lead to the formation of a structured interface, which can further influence properties like viscosity, surface tension, and electrochemical stability. The resulting nanostructuring is crucial in determining the catalytic and transport properties of ionanofluids in various reactions.

The relationship between ionic liquids and nanoparticles is complex and critical for the design of efficient ionanofluids (Lee *et al*., 2025). The properties of the ILs can influence the dispersion, stability, and reactivity of nanoparticles, while their nature can modify the solvation and ionic characteristics of the ionic liquid. For instance, the functionalisation of nanoparticles with ligands or surfactants can improve their dispersion in the IL, thereby enhancing the overall performance of the ionanofluid. Conversely, the presence of nanoparticles can impact on the ionic liquid's viscosity, conductivity, and stability, highlighting the interdependence between the two components.

Synthesis Techniques

The synthesis of ionanofluids involves various methods that aim to combine ionic liquids effectively with nanoparticles while maintaining their individual properties (Zhang *et al*., 2025). The two most common techniques for preparing ionanofluids are physical mixing and in situ synthesis. Each approach has its advantages and challenges, particularly in terms of scalability, reproducibility, and the final properties of the material.

Physical Mixing*:* Physical mixing is the simplest and most widely used method for synthesising ionanofluids (Duarte *et al*., 2024). In this process, nanoparticles are directly added to the ionic liquid under controlled conditions. Typically, the nanoparticles are dispersed in the IL using mechanical stirring, sonication, or high shear mixing, ensuring a homogeneous distribution of the particles within the liquid (Figure 2). This method is highly efficient and cost-effective, particularly when commercially available nanoparticles are used. However, achieving stable dispersion of nanoparticles in ionic liquids can be challenging due to the strong interactions between the IL and the particles, which can lead to aggregation or settling of nanoparticles over time (Kulshrestha, Kumar & Sharma, 2024). To overcome this, surfactants or stabilising agents are often added to improve the dispersion and stability of the nanoparticles.

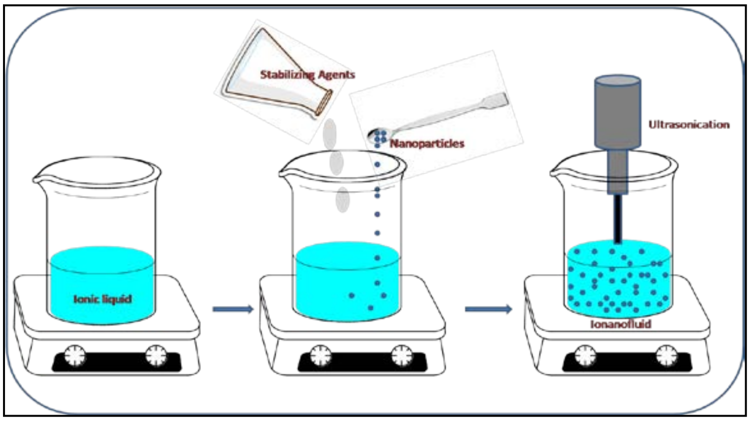

Figure 2: Schematic Representation of the Synthesis of Ionanoliquid by Physical Mixing

In Situ Synthesis*:* In situ synthesis involves the formation of nanoparticles directly within the ionic liquid matrix. This approach typically involves the reduction or precipitation of metal or metal oxide nanoparticles from precursor salts or complexes (Yang *et al*., 2025). By controlling the reaction conditions (e.g., temperature, time, and concentration of precursors), nanoparticles can be synthesised with precise control over their size, shape, and distribution within the ionic liquid. In situ synthesis often results in better nanoparticle-IL interactions and more stable dispersion, as the nanoparticles are formed within the IL environment. This method also eliminates the need for additional stabilisation agents, as the ionic liquid itself can act as a stabilising medium (Dupont *et al*., 2024).

However, controlling the size and uniformity of the nanoparticles can be more challenging compared to physical mixing, especially for complex or highly reactive nanoparticles.

Stabilisation Mechanisms*:* A critical aspect of ionanofluid synthesis is ensuring the long-term stability and uniform dispersion of nanoparticles in ionic liquids (Urmi *et al*., 2021). This is particularly important for catalytic applications, where the size, shape, and distribution of nanoparticles significantly impact the reactivity and efficiency of the system. Stabilision mechanisms include electrostatic stabilisation, steric stabilisation, and hybrid approaches that combine both. Electrostatic stabilisation relies on the repulsive forces between charged nanoparticles and the ionic liquid ions to prevent aggregation (Khavani, Mehranfar & Mofrad, 2022).

Steric stabilisation, on the other hand, involves the use of surfactants or ligands to create a physical barrier around the nanoparticles and prevent their agglomeration. In some cases, hybrid stabilisation methods are used to enhance both electrostatic and steric repulsion, ensuring long-term stability.

***Challenges in Scalability and Reproducibility**:* While ionanofluids show great promise in various applications, scaling up their synthesis for industrial applications presents significant challenges. Achieving uniform dispersion of nanoparticles in large volumes of ionic liquids is difficult, as agglomeration tends to increase with the scale of the system (Hu *et al*., 2023).

Additionally, the synthesis process often requires precise control of reaction conditions, which can be difficult to maintain in large-scale operations. Reproducibility is another challenge, as small variations in the synthesis procedure can result in significant differences in the properties of the final ionanofluid, affecting its performance in catalytic and other applications. Developing more efficient and scalable synthesis methods, such as continuous flow reactors or automated systems for nanoparticle functionalization, will be essential for the broader adoption of ionanofluids in industrial settings.

Comparison with Conventional Solvents and Nanofluids

Ionanofluids offer several advantages over conventional solvents and traditional nanofluids, particularly in the context of sustainability and catalytic efficiency (Paul *et al*., 2021). When compared to water and organic solvents, ionanofluids demonstrate superior stability, higher thermal conductivity, and tunable properties that can be optimized for specific applications.

***Advantages over Water and Organic Solvents**:* Water, although widely used as a solvent, has limitations in terms of its thermal stability and chemical reactivity (Mondal, Kundu & Mandal, 2024). Many chemical processes require solvents that can operate at high temperatures or under harsh conditions, where water would either boil off or undergo decomposition. Organic solvents, while more stable than water, often exhibit high volatility, toxicity, and environmental hazards, making them unsuitable for sustainable chemistry applications. In contrast, ionic liquids, which are non-volatile and thermally stable, offer a safer and more efficient alternative. Ionanofluids, by combining ionic liquids with nanoparticles, can further enhance the performance of these materials, enabling reactions to take place under more efficient and controlled conditions (Swapna *et al*., 2024).

Additionally, ionic liquids are inherently less toxic and can be designed to be biodegradable, aligning with the principles of green chemistry.

***Advantages over Traditional Nanofluids**:* Traditional nanofluids are typically composed of nanoparticles suspended in conventional liquids, such as water or oils. While these nanofluids exhibit enhanced thermal conductivity and catalytic properties compared to pure liquids, they suffer from issues like poor stability, aggregation of nanoparticles, and limited tunability of the solvent. In contrast, ionanofluids offer better stability due to the interaction between the nanoparticles and the ionic liquid medium, which reduces aggregation and ensures better long-term performance (Xu *et al*., 2024). The ionic nature of the solvent also allows for greater control over the solvation environment, enhancing the dispersion and reactivity of nanoparticles.

Furthermore, ionanofluids can be tailored for specific applications by adjusting the ionic liquid's structure, which is not possible with traditional nanofluids.

Role of Lonanofluids in Sustainable Chemistry

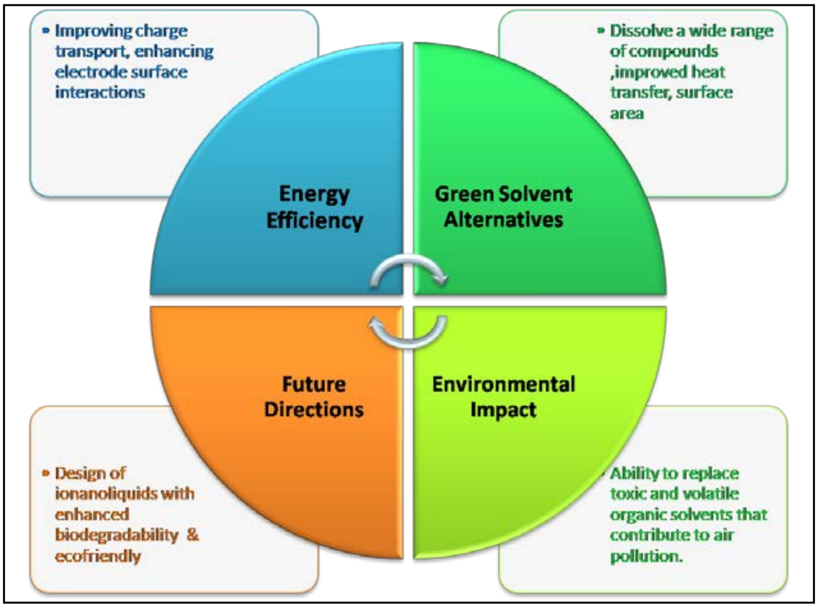

Figure 3: Represents the Various Roles of Ionanofluids in Sustainable Chemistry

Green Solvent Alternatives

The increasing global awareness of environmental issues and the need for sustainable chemical processes has driven the development of green solvents (Ullah, Haseeb & Tuzen, 2024). Traditional solvents, especially volatile organic compounds (VOCs), have significant environmental drawbacks, such as high toxicity, flammability, and the potential to cause air pollution and environmental contamination. The use of volatile solvents in various chemical processes contributes to the release of harmful emissions and poses challenges in waste disposal. In this context, ionanofluids, which combine ionic liquids (ILs) with nanoparticles, offer an effective alternative for sustainable solvent systems, addressing many of the issues associated with conventional solvents.

Lonic liquids are a class of solvents composed entirely of ions, which are characterized by their negligible vapor pressure, high thermal stability, and tunability of physicochemical properties (Vishwakarma *et al*., 2025). The non-volatile nature of ionic liquids makes them ideal for processes that would otherwise rely on volatile organic solvents. By introducing nanoparticles into these ionic liquids, ionanofluids not only retain the favorable properties of ILs, such as their ability to dissolve a wide range of compounds, but also gain enhanced properties like improved heat transfer, increased surface area, and better catalytic behavior. As a result, ionanofluids can serve as effective green alternatives to volatile solvents, offering improved efficiency and environmental benefits (Figure 3).

A notable example of ionanofluids used in green extraction processes is their application in liquid-liquid extractions (Khan *et al*., 2024). In the extraction of bioactive compounds from plant materials, ionanofluids have been successfully used as solvents for green extraction techniques, such as microwave-assisted and ultrasonic-assisted extraction. In these processes, the ionic liquids in the ionanofluids provide excellent solubility for a wide variety of polar and non-polar compounds, making them ideal for selectively extracting bioactive compounds without the need for toxic organic solvents. The addition of nanoparticles enhances the extraction process by providing additional surface area for solute interaction and improving the overall efficiency of the extraction (Khoramian *et al*., 2024).

Furthermore, ionanofluids have been explored in the field of separation processes, such as the separation of rare-earth elements and precious metals. In traditional processes, organic solvents are often used for solvent extraction or precipitation, leading to the generation of toxic waste. Ionanofluids, due to their tunable properties and the possibility of adjusting the interaction between the ionic liquid and nanoparticles, can be optimized for specific separation processes, thus improving the selectivity and efficiency of separations while minimizing waste generation. Additionally, the recyclability of ionanofluids further enhances their sustainability, as they can often be reused multiple times without a significant loss in performance (Mao *et al*., 2025).

Energy Efficiency

Ionanofluids have gained significant attention for their role in improving the energy efficiency of various processes, particularly in electrochemical reactions and energy storage applications. One of the major advantages of ionanofluids in sustainable chemistry is their ability to operate under lower energy demands, thus contributing to energy savings in industrial processes and reducing the overall environmental impact. This is especially relevant in processes that require precise temperature control or involve energy-intensive operations.

In electrochemical reactions, such as those used in batteries, fuel cells, and supercapacitors, energy efficiency is a critical concern (Raza *et al*., 2024). Ionic liquids, due to their high ionic conductivity and thermal stability, have already demonstrated their potential to enhance the performance of electrochemical devices. When combined with nanoparticles to form ionanofluids, these systems can offer even greater advantages by improving charge transport, enhancing electrode surface interactions, and promoting better heat management. The addition of nanoparticles, particularly metal and metal oxide nanoparticles, can further improve the electrochemical performance by providing additional active sites for reactions, thereby enhancing the efficiency of energy conversion and storage (Pazhamalai *et al*., 2024).

For instance, in fuel cells, ionanofluids have been employed as electrolytes or catalysts, replacing conventional organic electrolytes or acids, which are prone to corrosion and degradation over time. The high thermal conductivity of ionanofluids facilitates better heat management, ensuring that the system remains within optimal operating conditions and reduces the energy required for cooling. In energy storage systems such as lithium-ion batteries, the use of ionanofluids as electrolytes can improve the cycling stability and efficiency of the battery, resulting in higher performance over longer periods (Joseph & Mathew, 2025). The addition of nanoparticles can also improve the conductivity of the electrolyte, allowing for faster charge and discharge cycles while maintaining stability and reducing energy losses.

In addition to electrochemical applications, ionanofluids have shown promise in reducing energy demands in various industrial processes, such as catalytic reactions and heat exchange systems. Their enhanced thermal conductivity, a result of the interaction between nanoparticles and the ionic liquid, allows for more efficient heat transfer, reducing the need for external heating or cooling sources. This leads to lower energy consumption and improved process efficiency, particularly in energy-intensive industries like petrochemicals, refining, and chemical manufacturing.

The incorporation of ionanofluids into sustainable energy systems holds immense potential for improving energy efficiency across various sectors, from industrial manufacturing to renewable energy applications (Hai *et al*., 2024). By reducing the energy required for key processes, ionanofluids can contribute significantly to minimizing the environmental footprint of energy production and consumption.

Environmental Impact

The environmental impact of chemical processes is a central concern in the field of sustainable chemistry, and ionanofluids offer several advantages that contribute to reducing emissions, waste generation, and overall ecological harm (Razzaq *et al*., 2025). Their unique properties, such as non-volatility, recyclability, and biodegradability, make them a promising solution for reducing the environmental footprint of industrial processes.

One of the primary benefits of ionanofluids in reducing environmental impact is their ability to replace toxic and volatile organic solvents that contribute to air pollution and hazardous waste generation. Conventional organic solvents are often harmful to both human health and the environment, and their disposal typically involves complex procedures to mitigate toxicity. Ionic liquids, on the other hand, are designed to be less toxic, non-volatile, and chemically stable, making them safer alternatives. The incorporation of nanoparticles into ionic liquids to form ionanofluids further enhances their environmental profile, as these systems are typically more stable and efficient, requiring less solvent and fewer chemical additives in processes (Mathew *et al*., 2024).

Ionanofluids also contribute to reducing waste generation in catalytic processes. Traditional catalytic systems often require large amounts of solvent or produce significant amounts of waste products that must be carefully handled. The use of ionanofluids in catalytic reactions allows for better control over reaction conditions, leading to higher selectivity and reduced byproduct formation. Furthermore, ionanofluids can often be recycled and reused multiple times, minimizing waste and reducing the need for fresh solvents or reagents (Tomar & Jain, 2022). This aspect is particularly important in industrial applications, where minimizing waste and recycling materials can significantly reduce operational expenses and environmental impact.

In addition to their role in reducing emissions and waste, ionanofluids are also being explored for their potential in sustainable energy applications. As mentioned earlier, the improved thermal conductivity and energy efficiency of ionanofluids can lead to reduced energy consumption in industrial processes, which in turn results in lower greenhouse gas emissions. By reducing the overall energy demand of chemical processes and energy storage systems, ionanofluids contribute to mitigating climate change and promoting the transition to cleaner, more sustainable energy sources.

Moreover, the environmental benefits of ionanofluids extend to their potential for biodegradability and recyclability (Gonçalves *et al*., 2021). Many ionic liquids, particularly those based on biocompatible or renewable sources, can be designed to break down into non-toxic byproducts over time. This property is critical for ensuring that ionanofluids do not pose long-term risks to ecosystems or human health. Ongoing research is focused on developing new ionic liquids and ionanofluid systems that are not only effective in their applications but also environmentally benign and easily recyclable. The biodegradability of ionanofluids adds another layer of sustainability, ensuring that they contribute to a circular economy rather than becoming a source of persistent waste (Anadebe *et al*., 2024).

Finally, the use of ionanofluids in environmental remediation processes, such as wastewater treatment and pollution control, further enhances their positive environmental impact. By improving the efficiency of water purification and pollutant removal, ionanofluids can help mitigate the environmental damage caused by industrial pollution and chemical contamination. The ability to tailor the properties of ionanofluids to specific contaminants allows for more targeted and efficient removal, reducing the need for harsh chemicals and minimizing the generation of secondary pollutants.

Future Directions in Sustainable Chemistry with Ionanofluids

Looking ahead, the potential for ionanofluids to play a transformative role in sustainable chemistry is vast. As the demand for more efficient, greener, and environmentally friendly chemical processes continues to rise, the development of ionanofluids will be central to achieving these goals (Mahian *et al*., 2021). Future research will likely focus on optimizing the synthesis and properties of ionanofluids to enhance their performance in specific applications, particularly in catalysis, energy storage, and environmental remediation.

One promising area of research is the design of ionic liquids with enhanced biodegradability and minimal environmental impact. As more ionic liquids are derived from renewable resources, their environmental footprint can be reduced even further. In addition, the development of more efficient nanoparticle-ionic liquid interactions could lead to the creation of ionanofluids with improved performance in catalytic reactions, separations, and energy applications. Innovations in nanomaterials, such as functionalized nanoparticles and hybrid nanostructures, could further enhance the properties of ionanofluids, making them even more versatile and effective in sustainable chemistry (Karatrantos *et al*., 2022).

The integration of ionanofluids into existing industrial processes is also expected to grow. By replacing conventional solvents with ionanofluids, industries such as pharmaceuticals, petrochemicals, and bioenergy can reduce their environmental impact while improving process efficiency. The continued development of scalable and cost-effective synthesis methods for ionanofluids will be key to their widespread adoption in industrial settings.

Applications in Catalysis

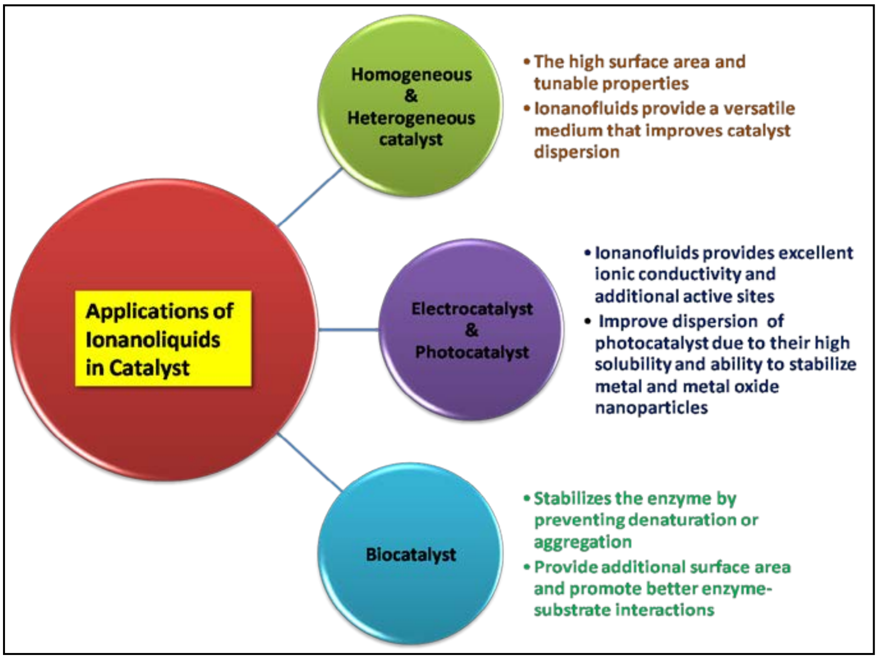

Figure 4: Represents the Different Catalytic Applications of Ionanofluids

Catalysis plays a crucial role in modern chemical industries, driving a wide range of reactions with higher selectivity and efficiency (Isahak & Al-Amiery, 2024). The integration of ionic liquids with nanoparticles to form ionanofluids offers exciting opportunities in the field of catalysis. These materials have been shown to enhance the performance of catalytic processes by improving reaction rates, selectivity, stability, and reusability. In this section, we explore the diverse applications of ionanofluids in catalytic systems, ranging from homogeneous and heterogeneous catalysis to electrocatalysis, photocatalysis, and biocatalysis (Figure 4). Additionally, we will examine their industrial applications and the advantages they offer in large-scale catalytic processes.

Homogeneous and Heterogeneous Catalysis

Ionanofluids have been found to significantly enhance both homogeneous and heterogeneous catalytic processes (Bashir *et al.*, 2024). Homogeneous catalysis typically involves a catalyst that is in the same phase as the reactants, often a liquid or solution, which enables efficient mixing and interaction with the reactants. In contrast, heterogeneous catalysis involves catalysts in a different phase, often solids, interacting with reactants in a gas or liquid phase. The combination of ionic liquids and nanoparticles to form ionanofluids offers unique advantages in both types of catalytic systems, primarily by enhancing the reaction rates and improving the selectivity of reactions.

In homogeneous catalysis, the use of ionic liquids provides a stable environment for catalysts, often enabling reactions that are not possible or are inefficient in traditional organic solvents (Migowski, Lozano & Dupont, 2023). The incorporation of nanoparticles into the ionic liquid matrix results in the formation of ionanofluids, which further enhance the catalytic activity and stability. The high surface area and tunable properties of nanoparticles improve the interaction between the catalyst and the reactants, leading to enhanced reaction rates. Furthermore, the unique properties of ionic liquids, such as their non-volatility, low vapor pressure, and high thermal stability, make them ideal for carrying out high-temperature reactions, particularly those involving sensitive or volatile reactants.

For heterogeneous catalysis, ionanofluids provide a versatile medium that improves catalyst dispersion and enhances the efficiency of catalytic reactions (Shaari *et al*., 2022). The nanoparticles within the ionic liquid environment allow for better interaction between the solid catalyst and reactants, promoting faster reactions and higher selectivity. Additionally, ionanofluids can be used to stabilize the catalyst, preventing deactivation or aggregation that is common in traditional solvents. The ability of ionanofluids to support both homogeneous and heterogeneous catalysis is an exciting feature, as it enables a broader range of reactions to be carried out under milder conditions, reducing the need for harsh solvents or extreme temperatures.

One key advantage of ionanofluids in catalysis is their reusability. Catalysts suspended in ionanofluids show improved stability and can be reused multiple times without significant loss in activity (Yadav, Gupta & Sharma, 2022). This capability is especially beneficial for industrial processes, where catalyst recycling can lead to reduced costs and improved sustainability. The ability to recover and reuse catalysts effectively makes ionanofluids a valuable tool for both academic research and industrial applications.

Electrocatalysis and Photocatalysis

Ionanofluids also play a critical role in electrocatalysis and photocatalysis, two important areas for energy production and environmental sustainability. Electrocatalysis involves the acceleration of electrochemical reactions, such as those used in fuel cells, batteries, and water splitting, while photocatalysis relies on light energy to drive chemical reactions, such as CO_2 reduction and water splitting (Ni *et al*., 2023). Both fields benefit significantly from the use of ionanofluids due to the unique properties of ionic liquids and nanoparticles.

In electrocatalysis, ionanofluids are used to enhance the efficiency of reactions such as hydrogen evolution, oxygen reduction, and CO_2 reduction, all of which are vital for energy storage and renewable energy production. The ionic liquid component in ionanofluids provides excellent ionic conductivity, while the nanoparticles, often metal or metal oxide-based, enhance the electrochemical properties by providing additional active sites for reactions. For instance, ionanofluids have been used in fuel cells to improve the performance of the anode and cathode catalysts, leading to increased efficiency in energy conversion

(Ghosh & Subudhi, 2022). The high thermal stability and low volatility of ionic liquids, combined with the conductivity-enhancing properties of nanoparticles, make ionanofluids highly effective in maintaining consistent performance in electrochemical devices.

A particularly promising application of ionanofluids is in water splitting for hydrogen production, an essential process for the development of clean hydrogen energy. Ionanofluids can facilitate both the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER), which are key to efficient water splitting (Subramaniam *et al*., 2024). The use of ionanofluids in this context enhances the reaction rates, stability, and durability of the electrocatalysts, making the process more efficient and cost-effective. The nanoparticles present in ionanofluids can improve the catalyst's surface area, while the ionic liquid can help stabilize the catalyst and prevent unwanted side reactions, leading to higher hydrogen production efficiency.

In photocatalysis, ionanofluids have been explored for their ability to enhance the dispersion and efficiency of photocatalysts (Malika & Sonawane, 2022). Photocatalysts, typically semiconductors such as titanium dioxide (TiO_2), are used in reactions like CO_2 reduction and water splitting under light irradiation. The dispersion of photocatalysts in a liquid medium is crucial for maximizing their efficiency, and ionic liquids help improve this dispersion due to their high solubility and ability to stabilize metal and metal oxide nanoparticles. Additionally, ionanofluids can be engineered to tune the properties of the photocatalyst, such as its bandgap, to improve light absorption and catalytic performance. These properties make ionanofluids an attractive medium for driving photocatalytic reactions, enabling more efficient energy conversion and environmental remediation.

Biocatalysis

Biocatalysis, the use of natural catalysts, such as enzymes, to carry out chemical reactions, is another area where ionanofluids are showing promise (Khan *et al*., 2022). Enzymes are highly selective catalysts that operate under mild conditions, making them ideal for many industrial processes, especially those involving complex organic molecules. However, enzymes are often limited by their stability, solubility, and reusability, which can hinder their broader application in industrial catalysis. Ionanofluids offer a solution to these challenges by providing a stable and supportive environment for enzymes, thereby enhancing their performance and longevity.

In ionic liquid-nanoparticle systems, the ionic liquid stabilizes the enzyme by preventing denaturation or aggregation, while the nanoparticles provide additional surface area and promote better enzyme-substrate interactions. This results in enhanced catalytic efficiency and improved stability of the enzyme over extended use. Ionanofluids have been successfully used in various enzymatic reactions, such as the hydrolysis of polysaccharides and the synthesis of biofuels (Shahbaz *et al*., 2022). The tunable properties of ionic liquids allow for the optimization of enzyme activity, as they can influence the polarity and viscosity of the medium, which in turn affects enzyme conformation and activity.

Case studies have demonstrated the effectiveness of ionanofluids in biotransformations. For example, in the production of biodiesel from triglycerides, enzyme-catalyzed reactions can be enhanced by using ionanofluids as the medium (Ong *et al*., 2021). The presence of nanoparticles can increase the surface area available for enzyme-substrate interactions, leading to faster reaction rates and improved conversion efficiencies. Additionally, the ability to recycle ionanofluids with minimal loss in activity makes them a viable option for large-scale industrial applications. This recyclability is a key advantage in reducing the overall cost of biocatalytic processes and ensuring their sustainability in the long term.

Industrial Applications

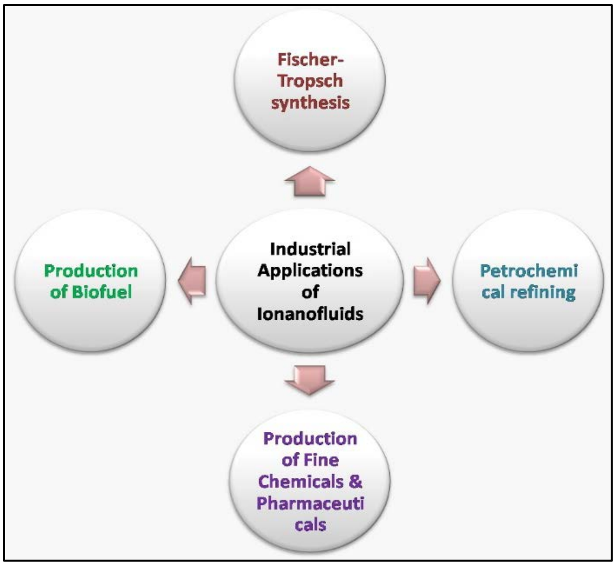

Figure 5: Represents the Various Industrial Applications

The use of ionanofluids in industrial catalysis is an exciting area of development, as they offer both economic and operational advantages in large-scale catalytic processes (Kumar *et al*., 2022). One notable example is their application in Fischer-Tropsch synthesis, a process used to convert syngas (a mixture of carbon monoxide and hydrogen) into liquid hydrocarbons. This process is essential for producing synthetic fuels, particularly in regions where natural oil resources are limited. The use of ionanofluids in Fischer-Tropsch synthesis improves the efficiency of the reaction by enhancing the dispersion of the catalyst and providing better control over reaction conditions (Teimouri *et al*., 2022). The high stability and non-volatility of ionic liquids also make them suitable for high-temperature catalytic processes, such as those involved in Fischer-Tropsch synthesis.

Another industrial application of ionanofluids is in petrochemical refining, where they are used to catalyze the cracking of large hydrocarbons into smaller, more valuable products (Figure 5). The presence of nanoparticles in ionanofluids improves catalyst activity and selectivity, which leads to higher yields of desired products and reduced byproduct formation. Ionanofluids also enhance heat transfer and reduce energy consumption in industrial processes, contributing to overall energy savings and improved sustainability (Elsaid *et al*., 2021). Furthermore, the ability to recover and reuse ionanofluids multiple times without significant loss in catalytic activity makes them cost-effective for large-scale operations.

Beyond these applications, ionanofluids have potential uses in other industrial catalytic processes, such as the production of fine chemicals, pharmaceuticals, and biofuels. In these industries, the ability to perform highly selective reactions under mild conditions is critical for improving product yields and reducing environmental impact. Ionanofluids offer a promising solution by providing a more efficient medium for catalytic reactions, reducing waste, and improving reaction efficiency (Obalalu *et al*., 2023). Their tunable properties, high stability, and recyclability make them an attractive option for a wide range of industrial applications, helping companies reduce costs while meeting sustainability goals.

Challenges and Limitations

Despite the promising applications and benefits of ionanofluids in sustainable chemistry and catalysis, there are several challenges and limitations that need to be addressed before their widespread adoption in industrial and commercial applications (Ikeuba *et a*l., 2024). These challenges primarily include the high cost and complexity of ionic liquids, toxicity concerns, stability issues of nanoparticles within ionic liquid matrices, and scalability concerns for large-scale industrial processes. Addressing these challenges is critical for maximizing the potential of ionanofluids and ensuring their long-term viability in both research and industrial settings.

High Cost and Complexity of Ionic Liquids

One of the primary barriers to the widespread use of ionanofluids is the high cost associated with the synthesis of ionic liquids (Minea & Sohel Murshed, 2021). While ionic liquids offer exceptional properties such as low vapor pressure, high thermal stability, and tunable viscosity, the complex synthesis methods required to prepare them can be expensive. Many ionic liquids are synthesized from petrochemical feedstocks, which can drive up their production costs. Furthermore, the need for specialized equipment and precise control over reaction conditions can make the synthesis process even more costly. Although advancements in the development of more cost-effective ionic liquids are underway, the high production costs remain a significant challenge for their widespread use in industrial applications (Kaur *et al*., 2025).

In addition to the cost of ionic liquids, the complexity of their synthesis can also limit the scalability of ionanofluids. Many ionic liquids require the use of rare or specialized chemicals, which may not be readily available in large quantities. The production of these materials in bulk at the industrial level can be difficult to achieve without significant modifications to existing manufacturing processes. To make ionanofluids a viable alternative to traditional solvents or catalytic systems, we must develop methods for producing ionic liquids on a larger scale in a cost-effective manner. Such development includes the identification of more abundant, cheaper raw materials and the optimization of synthetic routes to reduce time and cost. Without these advancements, the adoption of ionanofluids in large-scale applications will remain limited by their high production costs (Ali *et al*., 2021).

Toxicity Concerns and Need for Greener Alternatives

Another challenge facing ionanofluids is the potential toxicity of ionic liquids. While ionic liquids are often touted as "green solvents" due to their non-volatile nature and ability to replace traditional organic solvents, some ionic liquids can be toxic or harmful to human health and the environment (Inman, Nlebedim & Prodius, 2022). The toxicity of ionic liquids depends on their chemical composition, and certain ionic liquids have been shown to exhibit adverse effects on aquatic life, soil microorganisms, and human cells. The long-term environmental impact of using ionic liquids in large-scale applications is not yet fully understood, and there is a growing concern regarding the potential for accumulation and persistence in the environment (de Jesus & Maciel Filho, 2022).

To address these concerns, research is needed to develop more environmentally benign ionic liquids that are both effective and safer for industrial use. This involves the design of ionic liquids that are biodegradable and have minimal toxicity to ecosystems. Recent efforts have focused on developing ionic liquids derived from renewable resources, such as amino acids or sugars, which may offer a more sustainable and less toxic alternative. Furthermore, the use of ionic liquids with lower toxicity profiles could enhance the environmental credentials of ionanofluids, making them more appealing for green chemistry applications (Wei *et al*., 2021). Until safer and more eco-friendly ionic liquids are developed, the widespread adoption of ionanofluids will be hindered by these toxicity concerns.

Stability of Nanoparticles within Ionic Liquid Matrices and Scalability Issues

The stability of nanoparticles within ionic liquid matrices is another significant challenge for the practical application of ionanofluids (Hermida-Merino *et al*., 2021). Nanoparticles play a critical role in enhancing the catalytic properties of ionanofluids by providing additional surface area and active sites for reactions. However, the long-term stability of nanoparticles in ionic liquid environments can be an issue. Nanoparticles have a tendency to agglomerate or aggregate over time, particularly in the presence of ionic liquids with high viscosity or strong solvation effects. This aggregation can lead to a decrease in the catalytic efficiency of ionanofluids, as the active surface area of the nanoparticles is reduced (Main *et al*., 2021).

To address this challenge, researchers are exploring various stabilization techniques, such as functionalizing nanoparticles with surfactants or stabilizing agents to prevent aggregation. However, these methods can introduce additional complexities and may affect the overall performance of the ionanofluid. The development of more stable nanoparticle formulations, or the use of nanoparticles with inherent stability in ionic liquid matrices, will be essential for ensuring the long-term effectiveness of ionanofluids in catalytic processes (Ali *et al*., 2024).

Finally, the scalability of ionanofluids for industrial applications remains a major limitation. While ionanofluids have shown promise in laboratory-scale reactions, their scalability for large-scale processes is not yet fully realized. Challenges related to the cost of production, stability of nanoparticles, and the synthesis of large quantities of suitable ionic liquids all contribute to the difficulties in scaling up ionanofluids for industrial applications. In addition, the need for specialized equipment to handle and process ionanofluids may further complicate their integration into existing industrial processes (Greer, Jacquemin & Hardacre, 2020). Overcoming these scalability issues will require the development of efficient and cost-effective manufacturing processes, as well as a better understanding of the behavior of ionanofluids in large-scale systems.

Future Perspectives

The future of ionanofluids is promising, with advancements in ionic liquid design poised to unlock new applications and optimize their performance in various fields. One area of focus is the development of ionic liquids tailored for specific applications through precision molecular engineering. By modifying the chemical structures of ionic liquids, researchers can enhance their compatibility with specific nanoparticles, improving the stability and efficiency of ionanofluids in catalysis, energy storage, or separation processes. For example, ionic liquids designed with functional groups that interact selectively with target molecules or nanoparticles could significantly enhance reaction rates and product selectivity. Additionally, there is growing interest in using renewable and bio-based resources, such as lignin derivatives or amino acids, as precursors for ionic liquid synthesis. This approach not only aligns with the principles of green chemistry but also offers a pathway to reduce the cost and environmental impact of ionic liquid production.

Integrating ionanofluids with renewable energy systems and bio-based resources represents another promising avenue for future research. In energy storage, ionanofluids can improve the efficiency of batteries, supercapacitors, and fuel cells by enhancing ion transport and reducing resistance at interfaces. Moreover, their unique properties make them well-suited for use in renewable energy processes such as solar energy harvesting, CO_2 capture, and conversion. Coupling ionanofluids with bio-based catalytic systems could open new possibilities for biotransformations in sustainable chemical production. For instance, using enzymes stabilized within ionanofluids can improve the efficiency of biomass conversion into biofuels or bioplastics. Furthermore, leveraging ionanofluids in processes such as electrochemical water splitting or CO_2 reduction could help mitigate environmental challenges by promoting the transition to a carbon-neutral economy.

Advances in computational modeling and broader applications in areas like environmental remediation and healthcare will also play a pivotal role in shaping the future of ionanofluids. Computational tools can aid in the design of tailored ionanofluid systems by predicting their physicochemical properties and interactions with specific substrates or nanoparticles. These models can significantly accelerate the development of optimized ionanofluid formulations for targeted applications, reducing reliance on trial-and-error methods in the laboratory. Additionally, ionanofluids have immense potential for broader applications beyond catalysis and sustainable chemistry. In environmental remediation, they could be employed for the extraction and recovery of heavy metals, oil spills, or persistent organic pollutants. Their ability to stabilize biological molecules in healthcare provides opportunities for drug delivery, biosensors, and advanced medical diagnostics. By focusing on these future directions, researchers can expand the applicability of ionanofluids while addressing global challenges in sustainability, energy, and healthcare.

Conclusion

Ionanofluids represent a transformative advancement in sustainable chemistry and catalysis, offering unparalleled versatility and efficiency through the synergistic integration of ionic liquids and nanoparticles. Their unique physicochemical properties, such as high thermal stability, tunable viscosity, and enhanced ionic conductivity, position them as superior alternatives to conventional solvents and catalytic systems. Ionanofluids have demonstrated remarkable potential across diverse applications, including green solvent systems, energy-efficient catalysis, and environmental remediation. By reducing emissions, minimizing waste, and supporting the transition to renewable resources, ionanofluids align with the core principles of green chemistry and sustainable industrial practices. Despite their promise, challenges such as high production costs, toxicity concerns, nanoparticle stability, and scalability hinder their broader adoption. Addressing these issues requires the development of cost-effective and eco-friendly ionic liquids, improved nanoparticle stabilization strategies, and innovative manufacturing techniques to scale up ionanofluid production. Additionally, the environmental impact and long-term safety of these materials must be thoroughly assessed to ensure their compatibility with sustainable development goals. The transformative potential of ionanofluids can only be realized through interdisciplinary research that bridges chemistry, materials science, engineering, and computational modeling. Collaborative efforts to design tailored ionanofluid systems for specific applications, integrate them with renewable energy technologies, and expand their applications in healthcare and environmental remediation will be crucial. As the field advances, ionanofluids have the potential to revolutionize catalytic processes, enhance energy efficiency, and address critical environmental challenges, paving the way for a more sustainable future. By leveraging their unique properties and addressing current limitations, ionanofluids could redefine the landscape of sustainable chemistry and catalysis, fostering innovation across industries and scientific disciplines.

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