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Beningn Solvents: An Overview

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ABSTRACT

Benign solvents are environmentally friendly chemical solvents that are used as a part of green chemistry and can as well be known as green solvents. They came to prominence in 2015, when the UN defined a new sustainability-focused development plan based on 17 sustainable development goals, recognizing the need for green chemistry and benign solvents for a more sustainable future. They are developed as more environmentally friendly solvents, derived from the processing of agricultural crops or otherwise sustainable methods as alternatives to petrochemical solvents. The conventional solvents used in chemical, pharmaceutical, biomedical and separation processes represent a great challenge to green chemistry because of their toxicity and flammability. Water has been the most popular choice so far, followed by ionic liquids, surfactant, supercritical fluids, fluorous solvents, liquid polymers, bio-solvents and switchable solvent systems. Herein, we review the literature published in recent years on the classifications, characteristics, uses, pros and cons of benign solvents in various academic and industrial fields. There is a need to use eco-friendly benign solvents in various industrial applications to help minimize environmental pollution and economic cost.

KEYWORDS: Benign Solvent, Ionic Liquids, Supercritical Fluids, Sustainable, Environmental Pollution.

1. INTRODUCTION

Benign solvents are less harmful and less toxic green solvents used in place of petrochemical based solvents in order to reduce their harmful and toxicity effect to the environment and human health. Benign solvent is a reaction medium for different synthesis processes.[1] Most recently, petrochemical based solvents were the most common and perhaps the only choices of solvents among chemists. Some of them pose adverse effect on the human health and increase environmental cost.[2] They are extensively used in organic synthesis and a matter of much concern due to their characteristics such as high flammability, volatility and toxicity.[3] This scenario has been changed due to the intensive research towards environmentally benign substitutes for volatile and toxic organic solvents. Benign solvents include supercritical fluids, ionic liquids, polyethylene glycol, low melting polymers, perfluorinated solvents, deep eutectic solvents and water etc. Now chemists have to deal with the challenges of reducing the environmental impact of the processes without losing their efficiency by using these benign solvents under the concepts of green chemistry, this has emerged as an important area of chemistry and has achieved outstanding progresses towards the development of benign reaction processes.[4]

2. CLASSIFICATIONS, EXAMPLES AND USES OF BENIGN SOLVENTS

Benign solvents can be classified based on their chemical nature and sources, they include

2.1. Bio-Based Benign Solvents

These are environmentally friendly solvents derived from renewable biological resources such as plants, animals, or microbes. Unlike traditional solvents, which are typically derived from petrochemical sources, bio-based solvents are made from naturally occurring substances, which makes them more sustainable and less harmful to the environment. They are increasingly being used in industrial and pharmaceutical applications as alternatives to volatile organic compounds (VOCs) and other hazardous solvents.[5]

(a). Characteristics of Bio-Based Benign Solvents:

These solvents come from renewable feed stocks like corn, soybeans, sugarcane and cellulosic biomass, it reducies the dependence on fossil fuels. Bio-based benign solvents are generally less toxic than conventional solvents, making them safer for both human health and the environment. They break down more easily in the environment, reducing the risk of long-term pollution. Bio-based benign solvents are applied in various industries in producing cleaning products, coatings materials, pharmaceuticals, agrochemicals, and as alternatives to conventional solvents in chemical processes.[6]

(b). Examples of Bio-based Solvents:

- **Ethanol**: This is produced from the fermentation of sugars in crops like corn or sugarcane.
- **Lactic Acid**: This is derived from the fermentation of biomass and used as a solvent in cosmetics, pharmaceuticals, and food industries.
- **Glycerol**: A bye-product of biodiesel production, used in many personal care and pharmaceutical products.
- **D-Limonene**: This is extracted from citrus fruits like orange and lime. It is often used as a natural solvent in cleaning products and degreasers.[7]

(c). Applications of Bio- Based Benign Solvents

Bio-based benign solvents are used in industries that prioritize sustainability, such as

- **Green Chemistry**: In the production of environmentally friendly chemical processes.
- **Cleaning Products**: As solvents in biodegradable cleaning agents.
- **Paints and Coatings**: To reduce the environmental impact of volatile organic compounds (VOCs) emissions from traditional paints.[7]

(d). Associated Risk of Bio- Based Benign Solvents

- **Cost and Performance**: Bio-based benign solvents offer environmental benefits however they are very expensive to produce and sometimes having varied performance characteristics compared to petrochemical-based solvents.[8]

2.2. Supercritical Fluids

Supercritical Fluids such as *supercritical* CO_2, are substances that exist at temperatures and pressures above their critical point, combining properties of gases and liquids. It is widely recognized for its non-toxic, non-flammable characteristics and its ability to replace harmful organic solvents in extraction processes.[7] Supercritical CO_2 is being increasingly used in green extraction processes for natural compounds like essential oils and bioactive molecules, offering an eco-friendly alternative to traditional solvent extraction.

(a). Key Characteristics of Supercritical Fluids (SCFs):

1. **Density Similar to Liquids**: SCFs can dissolve solutes effectively, acting as solvents for a wide range of substances.

2. **Viscosity and Diffusion Rates Similar to Gases**: They can penetrate porous materials more efficiently than liquids, enhancing extraction processes.
3. **Tunable Solvent Properties**: By adjusting temperature and pressure, the solubility of substances in supercritical fluids can be finely controlled.
4. **Environmentally Friendly**: SCFs, especially supercritical CO_2 ($scCO_2$), are non-toxic, non-flammable, and can replace harmful organic solvents in industrial applications.[9]

(b). Applications of Supercritical Fluids:

- **Extraction**: SCFs are commonly used for extracting flavors, fragrances, and pharmaceuticals, particularly in the food and pharmaceutical industries.
- **Chemical Reactions**: Supercritical fluids are used in chemical synthesis, catalysis, and polymerization, where their tunable properties improve efficiency and selectivity.
- **Green Chemistry**: Due to their minimal environmental impact, SCFs are integral to green chemistry initiatives that seek to reduce the use of hazardous solvents.[10]
- **Nanoparticle Synthesis**: SCFs are employed in producing nanomaterials due to their ability to dissolve and precipitate materials at controlled rates, resulting in uniform particle sizes.
- **Pharmaceutical and Food Processing**: Advances in supercritical fluid technology have enhanced its use in pharmaceutical crystallization and food processing, where it helps maintain product purity and reduce toxic residues.[11]

2.3. Ionic Liquids (ILs)

Ionic liquids are salts in a liquid state at room temperature. Due to their negligible vapor pressure, thermal stability, and tunable properties, they are considered green solvents. Common examples include 1-Butyl-3-methylimidazolium chloride.[6,12,14]

2.4. Deep Eutectic Solvents (DESs)

Deep eutectic solvents (DESs) are formed by mixing hydrogen bond donors and acceptors, leading to lower melting points. They are biodegradable, non-volatile, and less expensive to produce. They include choline chloride and urea mixtures which are used in various applications like metal extraction and biocatalysis.[15] It was first introduced in 2001 and obtained its name in 2003 having considered to be one of the most innovative products ever made in history, leading to massive advancements in all industries.[16] Due to their many similar properties to ILs, such as high thermal stability, low vapor pressure, and volatility, DESs are sometimes known to be a classification of ionic liquids (ILs). When comparing ILs to DESs, DESs have the benefit of being easily synthesize since they only require mixing, and no further purifications are needed, additionally they have a low production cost. On the other hand, the high viscosity and solid state of DESs at room temperature may be a little bit of an issue. However, the physicochemical features of DESs can be tailored by carefully selecting the suitable hydrogen bond acceptor and donor.[16]

2.5. Water as a Benign Solvent

Water is one of the most benign and sustainable solvents that is non-toxic, non-flammable, and readily available. Many chemical reactions, especially enzymatic processes, are now being optimized to take place in aqueous environments to reduce reliance on hazardous organic solvents.[7] The term "universal solvent" was coined for water because of its ability to form a solution with almost any substance.[17] Its molecular structure has both positive and negative sides, so it effectively binds with other molecules of the opposite charge. However, despite being the so-called solvent for all, it is highly regarded as the greenest solvent as it possesses the following qualities: abundant, natural, low-cost, ubiquitous, and ready for use.[17] The unique characteristics of water make it distinct from any other solvent. Their high heat capacity allows it to absorb heat from its surroundings and then dissipate it as a cooling effect under extreme exothermic conditions. As a desirable heat buffer, it maintains a persistent state by resisting change. In terms of acting as a solvent, it improved the chemoselectivity and regioselectivity of solutions while increasing the rate of the chemical reaction.[18]

3. GENERAL CHARACTERISTICS OF BENIGN SOLVENTS

Benign solvents which can as well be referred to as green or environmentally friendly solvents possess several key characteristics that distinguish them from traditional hazardous solvent.
These properties are the brain behind benign solvents playing a very important role in sustainable chemistry, contributing to greener industrial processes and the transition to a circular economy which aligns with the UN sustainable development goals.[19]
They possess these outlined characteristics.

1. **Low Toxicity**: These solvents are friendly to human health and the environment. They are designed to minimize exposure to harmful chemicals, unlike petrochemical based solvents such as toluene and chloroform.[8]
2. **Biodegradability**: Benign solvents are biodegradable, it poses no trait to the environment thereby minimizing soil and water contamination.
3. **Low Volatility**: These solvents often have lower vapor pressures, this characteristics minimizes the emission of volatile organic compounds (VOCs) that contribute to air pollution.[3]
4. **Renewable Sources**: Most of the benign solvents such as bio-based solvents and deep eutectic solvents (DESs) are derived from renewable resources like glycerol or other organic matter, reducing reliance on petrochemicals.
5. **Reusability and Recyclability**: Benign solvents are often designed to be recyclable within processes, which reduces waste and energy consumption during manufacturing.
6. **Reduced Environmental Impact**: These solvents aim to lower the carbon footprint and decrease the overall environmental damage during production, use, and disposal.[9,18]

4. CONCLUSION

The shift towards benign solvents represents an important advancement in the pursuit of sustainable chemistry. The chemical industry can significantly reduce its ecological footprint by replacing traditional petrochemical solvents with environmentally friendly alternatives such as bio-based solvents, supercritical fluids, ionic liquids, deep eutectic solvents, and water,. These solvents not only offer lower toxicity and enhanced biodegradability but also minimize the emission of volatile organic compounds (VOCs), thereby contributing to cleaner air and safer working environments. The classification of benign solvents highlights the diverse options available for various applications from extraction processes to chemical synthesis. The unique properties of each category, such as the tunable characteristics of supercritical fluids and the non-volatility of ionic liquids, enhance their utility across numerous industries, including pharmaceuticals, agrochemicals, and materials science. However, challenges remain in terms of cost and performance, particularly for bio-based solvents, which may not always match the efficiency of their petrochemical counterparts. Ongoing research and development are essential to optimize these alternatives, ensuring they can compete in a market where traditional solvents have been entrenched for decades. In conclusion, the development and implementation of benign solvents align with the principles of green chemistry and sustainability, offering promising solutions for reducing environmental impact and carbon footprint while maintaining the efficacy of chemical processes. The commitment to utilizing these innovative solvents is crucial for the transition to a more sustainable chemical industry and achieving broader environmental goals.

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