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SOLVENTS AND THEIR ROLE IN INDUSTRIAL SETTINGS

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ABSTRACT

Industrial solvent is a new generation of industrial cleaning chemicals that are safe for human use, environmentally friendly and have a long shelf life. Industrial solvents are used in many different industries, it is widely used in multiple fields such as chemical refining, chemical manufacturing, and electrical engineering, chemical analysis and other industrial applications. Industrial solvent is an extremely simple yet versatile product. Industrial solvents are used in various industries like oil & gas, chemical, pulp & paper, food industry and many more. In oil and gas industry, it helps to extract oil from deep layers of oil well. It is also used for refining crude oil and other oil products.

In chemical engineering, Industrial solvents are chemical compounds that have strong solubility in organic solvents. They may be used as household cleaners or solvent cleaners for pharmaceutical industry. They are used in petroleum refining process, chemical industry, electronics manufacturing and many others. The main advantage of industrial solvents is that they are chemically inert. That means they do not react with other chemicals in a complex reaction but remain unchanged under normal conditions to maintain their properties, and can be used as everyday cleaners when the concentration is lower. In fact, we can even say that different types of industrial solvents are distinguished by their purity. Industrial solvents are not only transparent; they also provide good traceability against other chemicals in the market. They can be found in paints, plastics, rubber and many other products. They are also used to clean up oil spills and environmental pollution. Also, for cleaning and polishing metal, plastic, glass, paper or other materials. They are also used in many non-metallic applications, such as cleaning up spilled food or animal waste. The main and important characteristics of industrial solvent are as follows: It costs less than liquids. It has a long working time. It is easy to use while cleaning machinery and other equipment without much damage to it.

The pursuit of sustainable chemical processes has prompted a substantial emphasis on the advancement and utilization of green solvents and reaction media. Conventional solvents and reaction conditions frequently present environmental and health risks, underscoring the necessity for alternative, environmentally friendly solutions. Green solvents, distinguished by their low toxicity, renewable origins, and minimal environmental footprint, present promising avenues to tackle these issues. This paper offers a comprehensive overview of green solvents, encompassing their classification, properties, and applications across various chemical processes. Practically all Industrial manufacturers largely rely on solvents for a multitude of tasks such as separations, facilitating chemical reactions leading to desired products via catalytic, non-catalytic and bio-catalysis routes. Conventional solvents, mostly carbon based, are toxic and dangerous to environment. Careful selection of solvents based on health and environmental safety considerations therefore plays a vital role in the entire chemical processes. Green chemistry and its concepts have been responsible for improvements in the capabilities of conventional solvents, with a new class of so-called master solvents, 'green' or 'designer' solvents, with little or milder ecological impact and other benefits like economic and productivity. Green technologies are

moving from an option to a must in modern industrial applications. Ionic liquids, supercritical fluids and deep eutectic solvents are being most actively investigated as potential green solvents, due to their unique properties and possibility of tuning their cation and anion moieties to make them task-specific. In the chemical industry, they are well established for innumerable processes and applications, such as reaction media for organic transformations, in separations and extractions, as electrolytes for electrochemistry, in biotechnology, absorption of gases (CO₂) and as catalysts in organic synthesis.

Keywords: Industry, Solvent, Environment, Chemicals, Separation, Chemicals.

1 INTRODUCTION

A solvent is a liquid, solid or gas that can dissolve another substance to form a homogeneous solution. In fact, solvents are often liquids and are widely used in industry, medicine, and daily life. The most typical example is water – the most common solvent on Earth, or organic solvents such as acetone, ethanol.

Solvents play an important role in adjusting viscosity, increasing solubility, or mediating chemical reactions. Therefore, understanding solvents helps us apply them more effectively in many fields. Solvent systems play a crucial role in industrial processes by facilitating the extraction, separation, and purification of valuable compounds from raw materials. Across industries such as petrochemicals, mining, and food processing, the selection of solvent systems significantly impacts operational efficiency, product quality, and environmental sustainability. Understanding the comparative effectiveness of different solvents is essential for optimizing processes, reducing costs, and minimizing environmental footprint. Solvent systems are integral to a diverse array of industrial processes, serving pivotal roles in the extraction, separation, and purification of valuable compounds from raw materials. The selection of an appropriate solvent plays a critical role in determining the efficiency, effectiveness, and sustainability of these processes across various industrial sectors. This study embarks on a comprehensive comparative analysis of solvent systems, focusing on their applications in three key industries: petrochemicals, mining, and food processing.

Organic solvents are constantly present in the pharmaceutical production processes. The pharmaceutical industry is one of the largest users of organic solvents per amount of the final product. They are usually used at any step of the synthesis pathway of an active substance or excipients, and some times during the drug product formulation process. Because of some physical and chemical barriers, organic solvents cannot be completely eliminated from the product by manufacturing practices, such as drying in an elevated temperature under decreased pressure or by lyophilization (freeze-drying). Usually, some small amounts of solvents may remain in the final product. They are called residual solvents (RS), also commonly known as organic volatile impurities (OVI). Additionally, a drug product may also become contaminated by organic solvents from packaging, warehouse storage, or from shipping and transportation. For toxicological reasons manufacturers aspire to minimize the number and number of solvents applied in a drug production. Apart from the fact that they have no therapeutical value and may be toxic, they may additionally accelerate decomposition of the product. Special directions published in pharmacopeias and ICH guidelines determine maximum allowable amounts of RS in pharmaceutical products.

In modern chemistry, the choice of solvents and reaction media plays a crucial role not only in the efficiency of chemical processes but also in their environmental impact. Traditional solvents, while effective in facilitating reactions and dissolving compounds, often pose significant challenges due to their toxicity, volatility, and adverse effects on human health and the environment (Joshi & Adhikari, 2019; Hansen & Wilbur 1994). However, with the growing recognition of the importance of sustainable development, the principles of green chemistry (Erythropel et al., 2018; Anastas & Warner, 2000) have emerged as a guiding framework for designing chemical processes that minimize environmental impact while maximizing efficiency and safety. Additionally, it explores the classification, properties, and examples of commonly used green solvents, highlighting their role in promoting environmentally friendly practices in the field of chemistry. Traditional solvents, such as chlorinated hydrocarbons, aromatic hydrocarbons, and volatile organic compounds (VOCs), have long been utilized in various chemical processes due to their solvating power and versatility. However, these solvents pose significant environmental and health risks. VOCs, for instance, contribute to air pollution and can have detrimental effects on human health, including respiratory problems and neurological disorders. Moreover, many traditional solvents are nonrenewable, derived from fossil fuels, and contribute to carbon emissions and the depletion of natural resources. In response to the environmental challenges posed by traditional solvents, the principles of green chemistry have gained prominence in recent years. Green chemistry emphasizes the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances, thus minimizing environmental impact and promoting sustainability. Green solvents (Capello, Fischer & Hungerbühler, 2007; Clarke et al., 2018) represent a fundamental aspect of green chemistry, offering sustainable alternatives to conventional solvents. These solvents are characterized by their low toxicity, minimal environmental impact, and renewable or biodegradable nature (Winterton, 2021; Byrne et al., 2016). By replacing traditional solvents with green

alternatives, chemists can significantly reduce the environmental footprint of chemical processes while maintaining high levels of efficiency and performance (Devi et al., 2020; Welton, 2015).

Solvents are ubiquitous and have a wide range of industrial and domestic applications. Conventional solvents, mostly organic or carbon base in nature, are general solvents that are routinely used for laboratory and industrial purposes because of their volatility, melting point, better dissolving power and yield. Apart from their direct exposure to laboratory and industrial workers, when released in environment and left untreated, these can cause significant potential hazards to environment and to human, living plants, and animals destroying most organs.

Industrial and manufacturing firms commonly rely on solvents for a multitude of tasks such separations, making products, cleaning and degreasing machinery and surfaces, working with materials such as coatings and paints, and facilitating chemical reactions. Since, 1990 European Solvent Industry Group is advising the EU countries to follow guidelines to improve air quality by contributing to the reduction of total volatile organic compound (VOC) and emissions. The Solvents Industry Association also offers advice and guidance to producers, distributors, and consumers of solvents to help to minimize the potential environmental impact. Most of the organic solvents are toxic, dangerous and damaging to the environment. Therefore, selecting a suitable solvent is a great challenge to the research community as its impact on the environment is not forecast able. Such solvents are continued to be still used in large amount. One of the important factors for choosing an improved solvents is the solvent properties rated by their health characteristics and environmental safety. In this context, Welton summarizes few ways to make the chemical process more sustainable with the solvents having following characteristics: (i) it must have dual role, (ii) the product quality should be higher, (iii) number of intermediate steps are reduced, (iv) a smaller number of by-products is formed, (v) and improve products. Hence, the careful selection of solvents plays a vital role in the entire industrial chemical processes. Neil Winterton published, a pictorial representation of solvents used in a variety of industrial applications in Europe in 2017. About 5 million tons are used by the European solvents industry alone. Byrne et al; have reviewed several general purposes published green solvent selection guides with the aim to reduce use of the most hazardous solvents. This article serves the purpose of explaining the role of these guides, and how these can be used most effectively to enhance the greenness of chemical processes, particularly in laboratory organic synthesis and the pharmaceutical industry.

2 REVIEW OF LITERATURE

The main aim of solvents in industrial settings is to facilitate various chemical processes by dissolving, diluting, or extracting materials. They play a crucial role in manufacturing, cleaning, and chemical analysis across diverse industries like pharmaceuticals, textiles, and automotive. Solvents are essential for tasks like dissolving active ingredients in drug formulations, cleaning machinery, and enabling chemical reactions.

By evaluating solvent types, extraction methods, and process parameters, the study aims to identify optimal solvent systems that enhance extraction efficiency while considering environmental and economic factors.

This study focuses on:

- **Industrial Applications:** Comparative analysis of solvent systems in petrochemicals (oil refining), mining (mineral extraction), and food processing (flavor extraction).
- **Solvent Types:** Evaluation of organic solvents, supercritical fluids, aqueous solutions, and other solvent categories based on their effectiveness and suitability for specific industrial processes.
- **Environmental and Economic Factors:** Assessment of environmental impact, economic feasibility, and operational efficiency associated with different solvent systems.

The history of analytical studies on comparative analysis of solvent systems spans several decades and involves significant advancements in understanding their applications and impact across various industries:

- **Early Studies and Development (Early 20th Century):** Solvents have been integral to industrial processes since the early 20th century, with initial studies focusing on basic properties and applications in chemical industries. o Researchers began comparing different solvent systems based on their solvency power, volatility, toxicity, and environmental impact.
- **Expansion in Industrial Applications (Mid-20th Century):** During the mid-20th century, industrial growth led to increased demand for effective solvent systems in sectors such as petrochemical refining, where solvents were crucial for extraction and purification processes. Comparative studies expanded to include petrochemicals, where solvent systems played key roles in refining crude oil and separating different hydrocarbon fractions.
- **Diversification and Environmental Concerns (Late 20th Century):** By the late 20th century, studies intensified with a focus on diversifying solvent use across industries like mining and food processing. o Environmental

concerns emerged, prompting comparative analyses to include assessments of solvent biodegradability, toxicity, and emissions.

- **Technological Advancements and Modern Applications (21st Century):** The 21st century saw advancements in solvent technology, including the development of green solvents that are safer and more sustainable. Analytical studies increasingly incorporated computational modeling and simulation techniques to predict solvent behavior and optimize industrial processes.
- **Current Trends and Future Directions:** Today, comparative analysis continues to evolve with a focus on enhancing solvent efficiency, reducing environmental impact, and complying with regulatory standards. Emerging trends include the application of solvents in pharmaceutical manufacturing, nanotechnology, and renewable energy sectors. Overall, the history of analytical studies on solvent systems reflects a trajectory from basic industrial needs to sophisticated analyses that consider environmental and economic factors. Ongoing research aims to further optimize solvent use across diverse industrial applications. The current trends in research on comparative analysis of solvent systems across industrial applications, including petrochemicals, mining, and food processing, are characterized by several key developments:

The current trends in research on comparative analysis of solvent systems across industrial applications, including petrochemicals, mining, and food processing, are characterized by several key developments:

Green and Sustainable Solvents: There is a growing emphasis on developing and evaluating green solvents that are environmentally friendly, biodegradable, and less toxic compared to traditional solvents. Research focuses on assessing the performance of green solvents in various industrial processes to replace conventional solvents that pose environmental risks.

Computational Modeling and Simulation: Advances in computational techniques allow for predictive modeling of solvent properties and behaviors. This includes molecular dynamics simulations, quantum chemistry calculations, and machine learning approaches. Researchers use these tools to optimize solvent selection and process design, aiming for improved efficiency and reduced environmental impact.

Multi-functional Solvents: There is an interest in developing solvents that can perform multiple functions within industrial processes. For example, solvents that not only dissolve substances but also aid in separation, extraction, and catalysis. Studies explore the versatility of solvents across different industries to streamline processes and enhance overall efficiency.

Focus on Industrial Applications and Efficiency: Current research continues to focus on optimizing solvent systems for specific industrial applications such as petrochemical refining, mining extraction, and food processing. Efforts are directed towards improving solvent efficiency, reducing energy consumption, and minimizing waste generation in these sectors.

Three types of waste materials namely; substances such as starch and vegetable oils and wastes derived from lignocellulosic biomass, used cooking oils from food industry and fuel oil –a byproduct of ethanol manufacturing process from sugars, are the key sources for the recovery of various solvents and other valuable products. In addition, they do support environmental conservation as well. Integrated bio refineries combine many processes in sequence to valorize lignocellulosic biomass into value-added products. Integrating appropriate processes enhances the yield, reduces the reaction time, cost-effective, and sustainable. This approach also supports new products and paves its path towards sustainability in the framework of the circular economy. These refineries exploit food base substances to make ethanol, lignocellulosic waste into solvents like 2-methyletetrahydrofuran and esters of levulinic acids. These solvents have the potential to replace solvents like tetrahydrofuran, toluene, dichloromethane and diethyl ether in many applications. Fuel oil (a non-ideal mixture) is used to isolate C-6 alcohols and other fragrances and flavor ingredients. For obtaining isoamyl alcohol from fuel oil, use of dividing wall column indicates significant energy and economic savings compared to conventional configuration. Other green solvents such as isoamyl acetate or isoamyl carbonate could also be obtained. Mazubert A. et al; have reviewed the intensification of fatty acid methyl esters (FAME) production from waste cooking oil (WCO) using innovative process equipment. In particular, it addresses the intensification of WCO feedstock transformation by transesterification, esterification and hydrolysis reactions along with-it catalyst choice and product separation.

3 INDUSTRIAL SOLVENTS

The most common industrial solvents are alcohols and ethers. These solvents are used in various fields such as electronics, chemical industry, pharmaceuticals and food industry.

There are two kinds of solvents they are organic solvents and also inorganic solvents. Inorganic solvents are those solvents which do not have carbon such as water, ammonia whereas natural solvents are those solvents which consist of carbon and also oxygen in their composition such as alcohols, glycol ethers. This article has compiled some of the most common industrial solvents in use today: 1,2-Dichloroethane is an organic solvent and is an important industrial solvent because of its low volatility towards air, its ability to evaporate off when exposed to light, it is also very cheap and widely used as a solvent. It can be used as a solvent for many different applications such as; In terms of inertness, 1,2-Dichloroethane (1,2-DCE) is one of the few low-viscosity solvents that has been shown to be safe. The main disadvantage of 1,2-Dichloroethane is its volatility which makes removing it from an enclosure difficult. In some cases, it also has a tendency to react with organic compounds and cause harmful fumes.

Itaconic acid is an organic solvent which is used in the manufacturing of plastics, rubber and cosmetics. Itaconic acid can be found in the following: Itaconic acid is one of two organic compounds which are known as thioesters. The other compound is so called esterification product of itaconic acid, called itaconate.

Sodium Xylene sulfonate is a colorless viscous liquid or powder, a new type of high-efficiency and low-toxicity detergent solubilizer conditioner. It is a powerful chemical which can be used to dissolve metal, ceramic and non-metallic materials through oxidation. Sodium Xylene sulfonate is widely used in chemical industry because of its high efficiency, low toxicity and low cost. It can dissolve metal, ceramic and non-metal materials like stainless steel, ferrosilicon, brass materials etc., at room temperature or below the temperature of boiling water.

- There are common solvents and their chemical formulas:
- Methanol (CH_3OH): Used in fuel, chemical production.
- Xylene (C_8H_{10}): Used in paint, plastic.
- Toluene (C_7H_8): Used as an industrial solvent, glue production.
- Isobutanol ($(\text{CH}_3)_2\text{CHCH}_2\text{OH}$): Used in paint and biofuel.
- Ethanol ($\text{C}_2\text{H}_5\text{OH}$): Alcohol production, extraction solvent.
- Acetone ($\text{C}_3\text{H}_6\text{O}$): Cleaning, plastic production.

Solvents are chemicals that can be used to help you solve problems. They include many things like alcohol, acetone, gasoline, and paint thinner. But there are many solvents that can be harmful to your health in different ways. Here are 3 ways that industrial solvents can harm the human body:

Inhalation: This is the easiest way in which solvents are harmful to you. Because they are absorbed by your lungs and then into your body, they can cause a number of respiratory problems such as asthma. The most common reason for inhalation is due to car exhaust fumes and any work that requires you to wear respirators.

Skin Exposure: Many industrial solvents leave your skin dry and flaky, which can result in rashes, bumps and burns. So, if you're working with chemical solvents or paint thinner, you need to be cautious about how much of the solvent is applied on your skin.

Eye Exposure: Many industrial solvents can cause eye problems; this mostly happens when they evaporate on clothing or skin. If you're using solvent for cleaning or painting, you need to be careful about how much solvent is applied on your clothes and skin as well. Make sure to wear gloves and protective eyewear if your exposure to the chemicals is high enough.

Solvents are chemicals that are used to clean or remove stains from things. They can harm you in different ways, but most of them can be avoided.

4 IMPORTANCE OF SOLVENT SYSTEMS IN INDUSTRY

In industrial settings, solvent systems serve as versatile tools for extracting and isolating desired substances from complex matrices. The choice of solvent is influenced by factors such as solubility, selectivity, toxicity, and environmental impact. For instance, in petrochemical industries, solvents are crucial for refining crude oil into valuable products like gasoline and lubricants. In mining operations, solvent extraction techniques are employed to recover metals from ores, optimizing resource utilization and reducing environmental impact. Similarly, in food processing, solvents play a vital role in extracting flavors, colors, and bioactive compounds from natural sources, enhancing product quality and nutritional value.

5 APPLICATIONS OF GREEN SOLVENTS IN CHEMICAL PROCESSES

In recent years, there has been a growing emphasis on sustainability and environmental responsibility in the chemical industry. One area where significant progress has been made is in the development and application of green solvents and reaction media (Hessel et al., 2022; Sheldon, 2005). These environmentally friendly alternatives offer numerous benefits across various chemical processes, from solvent extraction and organic synthesis to polymerization and cleaning processes. In this article, we'll explore the applications of green solvents in chemical processes, with a focus on solvent extraction and separation techniques, organic synthesis and catalysis, polymerization and material synthesis, cleaning and degreasing processes and their importance as sustainable reaction media. Solvent extraction and separation techniques play a crucial role in various industries, including pharmaceuticals, mining and waste treatment (Brahmachari, 2015; Chaudhuri, Ghosh & Chattopadhyay, 2021). Traditional organic solvents used in these processes, such as chlorinated hydrocarbons and aromatic compounds, often pose significant environmental and health risks. Green solvents offer a safer and more sustainable alternative by reducing toxicity and environmental impact. For example, supercritical carbon dioxide (CO₂) has been widely used for extraction processes due to its low toxicity, non-flammability, and recyclability (Zorić et al., 2022; Gulzar et al., 2020). In organic synthesis and catalysis, the choice of solvent can profoundly influence reaction outcomes in terms of yield, selectivity, and reaction rate. Green solvents, such as water, ionic liquids, and fluorinated solvents, have emerged as viable alternatives to conventional organic solvents. Water, in particular, is abundant, cheap, and environmentally benign, making it an attractive solvent for a wide range of chemical processes, including hydrothermal reactions and aqueous-phase catalysis (Simon & Li et al., 2012). Ionic liquids, on the other hand, offer unique properties such as low volatility, high thermal stability, and tunable solvation properties, making them versatile reaction media for various catalytic processes (Tang et al., 2012; Greer, Jacquemin & Hardacre et al., 2020). Different fluorinated solvents are used for cell culture (Kasuya et al., 2011) and batteries (Narayan & Dominko et al., 2022). Polymerization and material synthesis represent another area where green solvents play a significant role in reducing environmental impacts. Conventional polymerization processes often rely on volatile organic solvents, which can contribute to air pollution and pose health risks to workers. Green solvents, such as bio-based solvents derived from renewable resources, offer a more sustainable alternative for polymerization processes. For example, bio-based solvents like ethanol and glycerol have been successfully used in the synthesis of biodegradable polymers and composites (Gu & Jérôme et al., 2013). Cleaning and degreasing processes in industries such as automotive, aerospace and electronics manufacturing typically involve the use of hazardous solvents like chlorinated hydrocarbons and petroleum-based solvents.

These solvents not only pose risks to human health and the environment but also contribute to air and water pollution. Green solvents, such as terpenes, d-limonene, and soy-based solvents, offer effective alternatives for cleaning and degreasing applications. These solvents are derived from renewable resources, are biodegradable and have low toxicity, making them environmentally friendly choices for industrial cleaning processes. In the pharmaceutical and agrochemical industries, the development of green solvents and reaction media is of paramount importance due to the stringent regulations and growing consumer demand for sustainable products. Green solvents offer several advantages in pharmaceutical and agrochemical synthesis, including improved reaction selectivity, reduced waste generation, and lower environmental impact. For example, the use of ionic liquids as reaction media has enabled the synthesis of pharmaceutical intermediates with higher purity and yield compared to conventional solvents (Petkovic et al., 2011). Deep Eutectic solvents are used for protein extraction (Bowen et al., 2022), in drug discovery (Oyoun et al., 2023) and cellulose dissolution (Chen et al., 2019). DES is the solvent for 21st century (Paiva et al., 2014).

6 SOLVENT PROPERTIES

Industrial solvents encompass a wide range of compounds with widely varying behaviour and properties. To classify all solvents unambiguously into discrete groups is an impossible undertaking. However, solvents can be classified according to specific properties from their chemical and physical characteristics, as well as environmental and health and safety considerations. Of course, many of these classifications are interconnected and overlapping.

6.1 Chemical properties:

Solvents can be broadly classified according to their chemical bonding. As well as organic solvents, water and supercritical carbon dioxide, which are primarily covalently bonded, there are ionic and metallic solvents. The consideration of metallic solvents is outside the scope of this chapter and ionic solvents will be considered only briefly.

Molten salts are ionic solvents that can be used to dissolve salts and metals. They are becoming increasingly important in both organic and inorganic reactions. Their physical properties, such as high thermal conductivity, permit rapid dispersal of heat in a reacting system.

6.2 Physical properties:

The selection of a solvent for a given reaction conditions is based on its important physical properties. For example, their dissolution characteristics make it possible to assess the use of a particular solvent for a chemical reaction, such as an extraction and properties such as evaporation as it reveals the potential emission of volatile organic compounds. Wikipedia lists some physical properties of green solvents falling in the categories like water, solvents derived from carbohydrates, waste materials, by extraction and that of propylene carbonate- a petrochemical solvent. For the remaining categories, some specific publications have described their properties in detail. For example, Nowosielski et al. carried out fundamental research by investigating important physical properties (density, speed of sound, refractive index, and viscosity) of both pure and aqueous solutions of a number of deep eutectic solvents. Benworth et al; examined Complex hydrogen bonding behavior of DESs, which is postulated as the root cause of their melting point depressions and physicochemical properties; to understand these hydrogen bonded networks. The rational selection of the appropriate ionic liquid solvent for a particular reaction requires general understanding of the properties of ionic liquids, and the details of some properties of the specific ionic liquid solvents being considered. John S. looked into solvent properties of ionic liquids that are relevant to catalysis. A roadmap for the literature values of density, viscosity, melting and glass transition temperatures, thermal stability, empirical solvent parameters, absorption, toxicity, surface tension, heat capacity, and thermal conductivity is provided. Fatty Acid Methyl Esters (FAME). Their physical characteristics are closer to those of fossil diesel fuels than pure vegetable oils, but properties depend on the type of vegetable oil. A mixture of different fatty acid methyl esters is commonly referred to as biodiesel, which is a renewable alternative fuel' ETIP-bio energy factsheet report comparison of fuel properties. FAME as compared to diesel is higher in density, lower in heating values, higher in viscosity, comparable in cetane number but lower in fuel equivalence'. It is also non-toxic and biodegradable. Some of the key properties of switchable solvents: are: High selectivity that helps in purification processes, low volatility, high stability and low reactivity, makes it easy to handle & storage, variable polarity allows for fine tuning of solvent properties, renewable attractive for green chemistry applications, non-toxic safer to use and handle and finally high solubility, useful for dissolving and extracting complex mixtures. In terms of quantitative values, the switchable properties are caused by two parameters namely: strength of their conjugate acid's pKa and octanol-water partition coefficient ratio Kow. They must have a pKa above 9.5 to be protonated by carbonated water and also a log (Kow) between 1.2 and 2.5 to be switchable because they will not be too hydrophilic or hydrophobic.

7 REMOVAL OF ORGANIC SOLVENTS

In the removal of undesirable organic solvents, the drying process is involved. Different drying techniques are commonly used in the pharmaceutical industry, such as: static bed drying (tray or truck ovens), fluidized bed drying, moving bed drying (turbo bed dryers) or spray drying. Other, less popular methods include dielectric (microwave) drying, tunnel drying and rotary current drying. Systems with vacuum, microwave or infrared drying have become more popular and sometimes their usage may be necessary. It should be pointed out that the drying process of substances containing organic solvents is dangerous and it is conducted under vacuum conditions. Usually a granulate, tablets or an active substance is placed in one of several types of dryers, then the dryer is sealed and a vacuum is applied, the temperature is elevated and nitrogen flows through the dryer. Some physical and chemical barriers that control solvent removal are sometimes so strong that additional actions have to be performed to remove reduce the amount of residual solvents. For this task extraction with supercritical CO₂ can be used. This technique is adapted to be used with polymeric microparticles and, unfortunately, is basically limited to slightly polar solvents. Also, there are some special cases where residual solvents are removed from therapeutic substances in different ways. A good example of this kind of procedure is radioactive holmium-166 loaded poly(L-lactic) microspheres, prepared with the use of chloroform by neutron irradiation in a nuclear reactor. High energy radiation (neutron irradiation or a gamma irradiation at a dose of 200 kGy) removes chloroform, which might have remained in the microspheres. As a result of radiolysis, chloroform is turned into chloride.

8 MAIN PROPERTIES OF GREEN SOLVENT DEVELOPMENT

Green solvents, also known as bio-based solvents, minimize environmental impact while still effectively working the way they're expected to. These alternatives aim to reduce reliance on fossil fuels, minimize toxicity, and enhance biodegradability. The overall goal of using these solvents is to contribute to a more sustainable and environmentally friendly industrial landscape. More about these key properties includes focusing on:

Environmental Friendliness—we derive green solvents from renewable resources, reducing dependence on fossil fuels. This promotes sustainability and minimizes carbon footprint.

Low Toxicity—unlike traditional solvents that may be harmful, green solvents exhibit lower toxicity, making them safer for both human health and the environment.

Biodegradability—bio-based solvents are often more readily biodegradable, reducing the risk of persistent environmental pollution.

Reduced VOC Emissions—Volatile Organic Compounds (VOCs) contribute to air pollution. Green solvents aim to have lower VOC emissions, improving air quality.

8.1 Other Types of Solvents

Industrial solvents are not just chemicals used in manufacturing processes. They are a cornerstone of modern industry that enables product creation, affecting many different industries. Recognizing and making the right choices about their usage is based on understanding and identifying how and when to use them. Solvents are usually categorized into three main types based on chemical composition:

8.1.1 Hydrocarbon Solvents:

These are derived from petroleum, including aliphatic and aromatic solvents, and are commonly used in paints, coatings, and cleaning products. Aliphatic solvents, known for their straight-chain structure, find extensive use in cleaning products, where their excellent solvent properties help break down contaminants effectively. Aromatic solvents, with their ring-shaped molecular structure, are commonly employed in paints and coatings because of their ability to dissolve resins and pigments, contributing to the formulation of high-quality finishes.

8.1.2 Oxygenated Solvents:

These solvents contain oxygen atoms and include alcohols, ketones, and esters. They are found in pharmaceuticals, cosmetics, and some industrial cleaning applications. Alcohols, such as ethanol and isopropanol, are prevalent in pharmaceuticals and cosmetics, serving as carriers for active ingredients and ensuring product stability. Ketones, including acetone, find applications in industrial cleaning, where their strong solvent properties make them effective in removing tough residues. Esters, with their pleasant fragrance, are often used in the formulation of perfumes and personal care products.

8.1.3 Halogenated Solvents:

These solvents contain halogen atoms, like chlorine or fluorine, and are frequently used in pharmaceuticals and as degreasers. The presence of halogen atoms enhances their effectiveness in breaking down and dissolving complex compounds, making them invaluable in pharmaceutical formulations. In degreasing applications, where the removal of stubborn residues is paramount, halogenated solvents prove their mettle. Their usage is also more targeted than other solvent types.

9 APPLICATIONS OF SOLVENTS

Solvents appear everywhere in modern life:

- Industry: As a paint thinner, ink, glue.
- Medicine: Production of drugs, extraction of medicinal herbs.
- Cosmetics: Dissolving essential oils, producing perfumes, cosmetics.
- Life: Cleaning (acetone in nail polish remover), cleaning surfaces.

To harness the benefits of industrial solvents responsibly, it is essential to delve into their properties and impact. Each solvent type possesses distinct characteristics that influence its suitability for specific applications. Factors such as volatility, toxicity, and biodegradability are crucial considerations in selecting the right solvent for a given task. Solvents find diverse applications across industries, each serving specific purposes:

9.1 Pharma

Solvents play a crucial role in drug formulation, extraction, and purification processes. They are critical in creating suspensions and emulsions. They're also used to extract active ingredients from raw materials in a way that will meet the industry's strict quality standards. Pharmaceutical industry accounts for mass consumption solvents in the range of 80–90%. Bio-solvents such as butanol, polyethylene glycol, bio-renewable solvents, and supercritical solvents are widely used in the extraction and solubility of drugs.

9.2 Cosmetics

Used in the formulation of skincare and beauty products, solvents help achieve desired textures and consistencies. Solvents are key players in the cosmetics industry, where the formulation of skincare and beauty products demands

precision. From creating fragrances to achieving the desired consistency in creams and lotions, solvents contribute to the aesthetic and functional aspects of cosmetic formulations.

9.3 Paints, Ink and Coatings:

Solvents contribute to the formulation of paints and coatings, aiding in spreading and drying processes. The world of colours and protective coatings relies heavily on solvents. In the formulation of paints and coatings, solvents help dissolve pigments, ensuring even distribution and promoting proper adhesion to surfaces. Their role extends to the printing industry, where inks are formulated to meet specific printing requirements.

9.4 Cleaning and Degreasers

Industrial cleaning and degreasing processes rely on solvents to act as powerful agents capable of dissolving and removing stubborn residues, such as grease, oil, and other contaminants that accumulate during regular operations. Whether it's cleaning machinery, degreasing surfaces, or ensuring the quality of manufactured components, solvents prove indispensable in maintaining operational efficiency. This thorough cleaning not only promotes the longevity of the machinery but also helps prevent potential malfunctions and breakdowns.

9.5 Agriculture

In the past two decades, supercritical fluids, ILs, and deep eutectic solvents have been the most actively investigated as possible green solvents, especially in the domains of food, flavor, and fragrance, as well as medicinal plant processing. Solvents are used in the formulation of pesticides and herbicides in the agricultural sector. These chemicals aid in creating effective solutions for crop protection, ensuring the health and productivity of agricultural endeavours. Organic carbonates are a family of organic molecules and chemical intermediates that are known for their high biodegradability, low toxicity, and flexibility which lead to their wide application in bio-catalysis.

10 SOLVENTS EFFECT ON REACTION RATES

In the light of the transition-state theory, solvent effects on rate constants depend on the relative stabilisation of the reactant molecules and the corresponding activated complex through solvation. The early pioneering work of Hughes and Ingold from about 1933 onwards laid the foundation of a classification of organic reactions with respect to the expected solvent influence on the reaction rate. Using a simple qualitative solvation model which allows only pure electrostatic interactions, they divided substitution and elimination reactions on the basis of different charge-type. When the passage to the transition state involves the creation or concentration of ionic charges, the activated complex will be more strongly solvated than the reactants. An increase in solvent polarity will therefore favour the transition state relative to the initial state, and a rate acceleration results with increasing solvent polarity.

Conversely, when the activation process involves disappearance or dispersal of charges, the reactants will be solvated more strongly in the initial state than in the transition state. A rate deceleration with increasing solvent polarity will result in this case.

A change in solvent polarity will have a negligible effect on the rate of reactions which involve little or no change in the charge density in going from reactants to the activated complex. A more general classification of organic reactions with respect to solvent effects, not restricted to substitution and elimination reactions, according to this scheme, organic reactions can be roughly divided into three classes depending on the character of the activated complex involved: dipolar, isopolar, and free-radical transition-state reactions.

Having discussed the solvent sensitivity of certain organic reactions, the question remains, which solvent property is responsible for the medium effects, and whether it is possible to describe these solvent effects in a more quantitative manner. Organic chemists usually attempt to understand solvent effects in terms of the 'polarity of the solvent'. It is, however, not easy to define this property precisely, and it is even more difficult to assess it quantitatively.

Seduced by the simplicity of electrostatic solvation models, attempts at expressing solvent polarity quantitatively usually involve physical solvent properties such as dielectric constant, dipole moment, or refractive index. But this procedure is often inadequate, particularly because it does not take into account specific solute-solvent interactions such as hydrogen bonding, charge-transfer forces etc.

Hence, from a more practical point of view, it seems reasonable to understand solvent polarity in terms of the overall solvation capability. This solvation capability of a solvent is in turn determined by the sum of all those molecular properties responsible for the solute-solvent interactions. It is obvious that solvent polarity, thus defined, cannot be described quantitatively by a single physical parameter. In such a situation other indices of solvent polarity are sought. The lack of comprehensive theoretical expressions for the calculation of solvent effects, and the inadequacy of defining

solvent polarity in terms of simple physical constants, has led to the introduction of purely empirical scales of solvent polarity. Based on the assumption that particular solvent-dependent chemical reactions or spectral absorptions may serve as suitable model processes, reflecting all the possible solute-solvent interactions in the solvation game, several empirical parameters of solvent polarity have been introduced recently by different authors.

This approach is very characteristic of the experimental chemist, but it is regarded with mistrust by theoretical chemists. However, organic chemistry has always made use of the qualitative, empirical rule that similar compounds react in similar ways, and that similar changes in the structure or in the reaction medium produce similar changes in the chemical reactivity.

One of the first verifications of this rule was the introduction of the so-called Hammett equation for the calculation of substituent effects on chemical reactivity, using the ionization reaction of substituted benzoic acids in water at 25 °C as a reference process. The various model processes used to establish such empirical scales of solvent polarity have been reviewed.

10.1 Bio-based solvents

Bio-based solvents are defined as solvents that are of renewable origin obtained by chemical or biochemical transformations of a wide range of biomass sources, such as (i) agricultural crops rich in carbohydrates (corn, wheat and sugar beets), (ii) forest products (e.g. wood), (iii) aquatic biomass (e.g. algae), and (iv) waste materials. They can be obtained through carbohydrate fermentation, extraction of vegetable oils and steam distillation of wood. The products of these processes include a wide range of compounds, such as alcohols, esters, glycerol's, terpenes, furfurals, and furans, some of which have the potential to be applied in green extraction processes due to their low miscibility with water, relatively high boiling point, and enhanced stability in comparison with the other solvents, as well as their low toxicity, biodegradability under normal environmental conditions, and solvent recyclability. However, the number of analytical procedures that utilize bio-solvents is still relatively low.

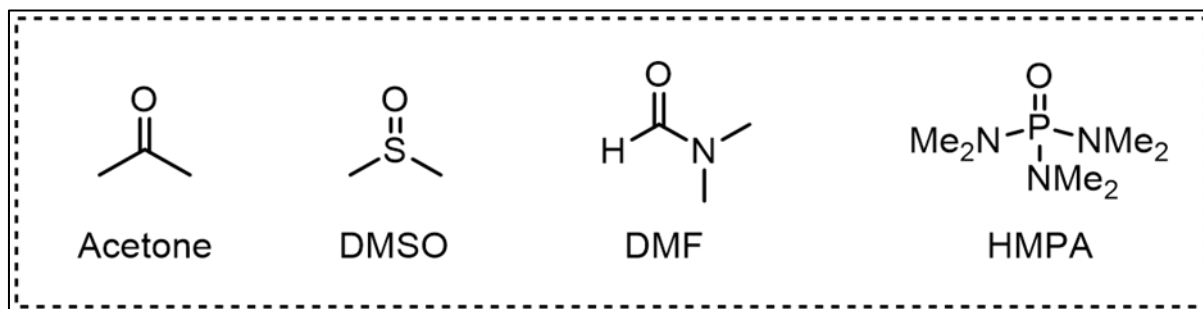
One of the most frequently used greener alternative solvents is d-limonene, extracted from the peels of citrus fruits mainly via steam-distillation or centrifugal separation. The first report on the use of this terpene for extraction was published by Mamidipally and Liu in 2004. In this case, the extraction of oil from rice bran samples was carried out in a comparison with the same extraction using hexane. The performance of the extraction and quality of the crude oil extracted were found to be comparable. Similar or even better results were also obtained in the extraction of fats and oils from olive seeds, lipids from salmon tissue, oil from microalgae, and fatty acids from grape seeds. Moreover, d-limonene has been successfully employed in place of other hazardous petroleum solvents, such as toluene and chlorinated organic solvents.

11 SOLVENT EFFECTS IN SUBSTITUTION REACTIONS

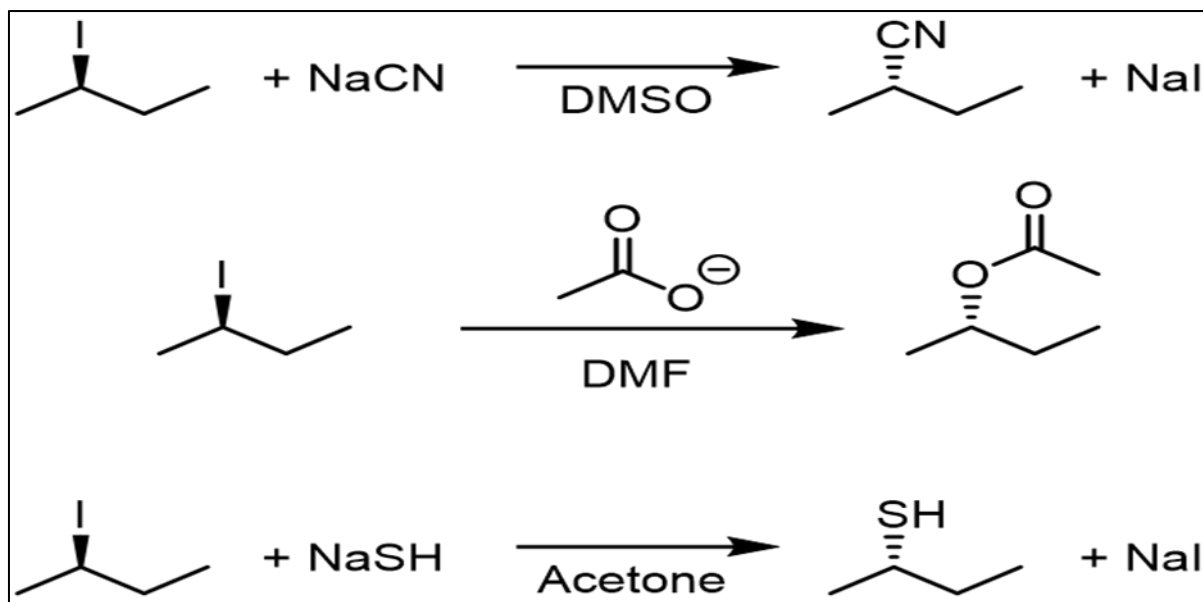
Solvent can have a big effect on the SN1 and the SN2 reaction since both reactions proceed through either a transition state or intermediate.

11.1 The SN2 reaction

The SN2 reaction has high-energy transition states which carry partial charges. To stabilize this transition state, it is best to use polar solvents without protons (remember, there are strong nucleophiles present). This is called a polar aprotic solvent. Examples include: acetone dimethyl sulfoxide (DMSO), dimethylformamide (DMF), hexamethylphosphoramide (HMPA),

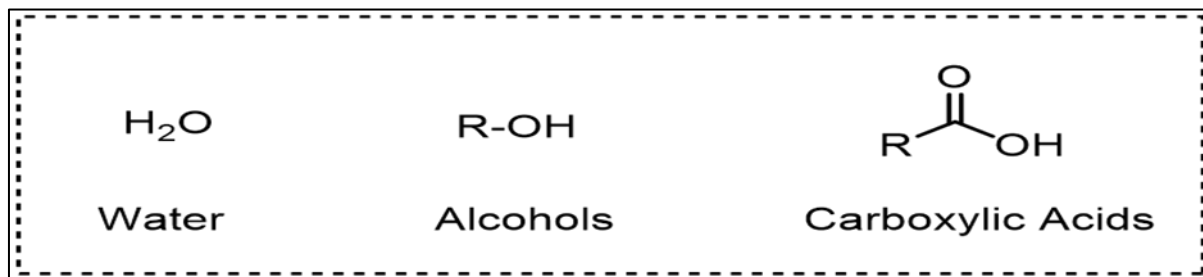


Examples reactions are shown below:



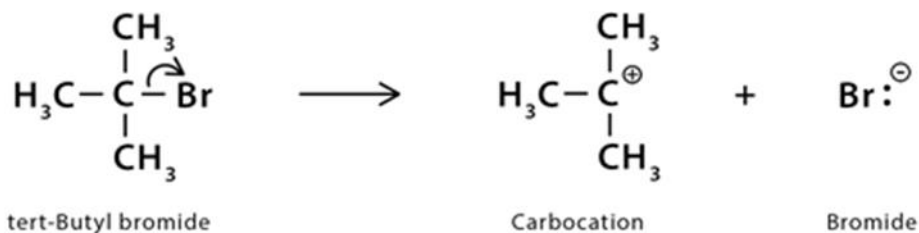
11.2 The SN1 reaction:

The SN1 reaction has carbocation intermediates which carry formal positive charges. To stabilize this intermediate, it is best to use polar solvents with protons (because the nucleophiles are weak)! This is called a polar protic solvent. Examples include: water (H₂O), alcohols (ROH, usually MeOH or EtOH) amines (usually NH₃) carboxylic acids (RCOOH, usually acetic acid).

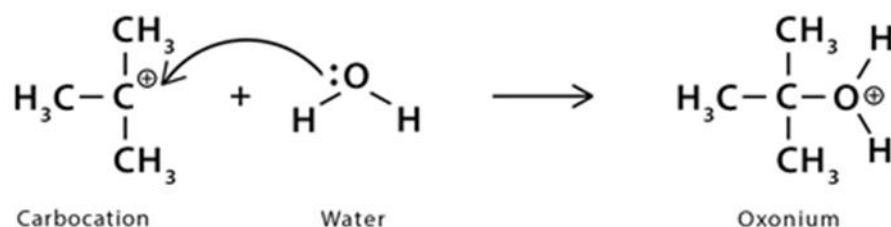


Mechanism of SN1 Reaction

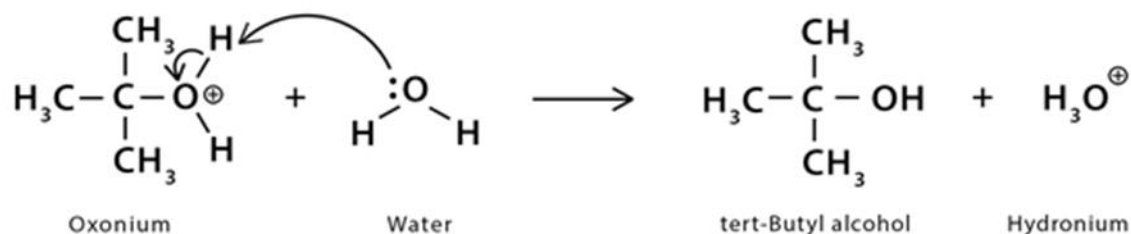
Step 1: Formation of a tert-butyl carbocation by separation of a bromide anion from the carbon atom of tert-butyl bromide.



Step 2: Nucleophilic attack of the carbocation by a water molecule, resulting in an oxonium ion intermediate.



Step 3: Deprotonation of the protonated nucleophile by a second water molecule, which acts as a base, resulting in an alcohol and a hydronium ion.



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An excellent leaving group Favors the SN1 reaction. A good leaving group is one whose bond with carbon can be easily broken and is, generally, a weak base. The order of reactivity of halides towards SN1 reaction is $\text{I}^- > \text{Br}^- > \text{Cl}^- > \text{F}^-$. In other words, the C-I bond is easy to break than the C-F bond, making the former susceptible to nucleophilic attack.

12 CHALLENGES TO THE WIDESPREAD ADOPTION OF GREEN SOLVENTS

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

13 CONCLUSION

Green solvents and reaction media play a pivotal role in advancing sustainable chemical processes, heralding a transformative shift towards environmentally conscious practices within the chemical industry. Their significance lies in their ability to mitigate the environmental impact traditionally associated with chemical synthesis while enhancing efficiency and safety. By substituting hazardous solvents with eco-friendly alternatives derived from renewable resources or possessing minimal toxicity, green chemistry principles are upheld, fostering a more harmonious

relationship between chemical production and the ecosystem. The adoption of green solvents and reaction media is imperative in addressing pressing environmental challenges such as pollution, resource depletion, and climate change.

These alternatives minimize the generation of harmful by-products, reduce energy consumption, and offer safer working conditions for personnel, thereby aligning chemical processes with sustainability goals. Moreover, their implementation promotes circular economy principles by facilitating the recycling and reuse of resources, contributing to the conservation of natural resources and reducing waste. To further propel the integration of green solvents and reaction media into mainstream chemical practices, continued research and innovation are paramount. Collaborative efforts among academia, industry, and government entities should be intensified to develop novel green solvents, optimize existing processes, and enhance their scalability and cost-effectiveness.

Additionally, educational initiatives should be bolstered to raise awareness among stakeholders about the benefits of green chemistry and foster a culture of sustainability within the chemical community. Looking ahead, envisioning a greener and more sustainable future in the chemical industry necessitates a steadfast commitment to green chemistry principles and the widespread adoption of environmentally benign practices. By embracing innovation, collaboration, and responsible stewardship, the industry can transition towards a circular economy model characterized by resource efficiency, waste reduction, and ecological integrity. Through concerted action and collective determination, we can pave the way for a thriving chemical sector that not only meets the demands of the present but also safeguards the well-being of future generations and the planet. Let us seize this opportunity to catalyze positive change and forge a path towards a truly sustainable future.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of Conflict of interest

The authors have no conflict of interest.

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