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Green Solvents in Chromatographic Techniques

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Abstract: *Chromatography is used extensively in various industries including, pharmaceuticals, environmental monitoring, food security and chemical construction. However, traditional chromatographic techniques are highly dependent on organic solvents which are often unstable, toxic, non-renewable and environmentally dangerous. Especially in relation to solvent selection, changes in green chemistry, permanent practices and regulatory requirements have been intensified with global care. Green solvents, such as deep eutectic solvents (DESs), supercritical fluid (SCF), ionic fluid (IL_S), and bio-based solvents are environmentally safe options that follow the principles of green chemistry. These solvents are characterised by properties such as low instability, high thermal and chemical stability, biodegradability and minimal toxicity. Their adoption in chromatographic methods not only reduces environment and health risks associated with traditional solvents, but also contributes to improving analytical efficiency and cost-efficiency. This paper presents a comprehensive review of the current landscape of green solvents in chromatographic techniques. It discovers the physical chemical properties, applications and comparable performance of various green solvents in liquid chromatography (LC), gas chromatography (GC), supercritical fluid chromatography (SFC), and other chromatographic formats. It also highlights recent innovations, major industrial and academic applications and regulatory ideas. While the integration of green solvents presents several advantages in which the consumption of the solvent is low, increased security, and compliance with environmental standards existing instrumentation, compatibility with limited solubility range, and with high initial costs are still needed to be addressed. Overall, paper underscores the transformative ability of green solvents in achieving permanent analytical practices and outlines strategic directions for future research and industrial implementation.*

Keywords: Green solvents, Chromatography, Low toxicity solvents, Solvent waste minimization, Biodegradability

I. INTRODUCTION

In analytical chemistry, chromatographic methods such as thin-layer chromatography (TLC), gas chromatography (GC), liquid chromatography (LC), and supercritical fluid chromatography (SFCs) are important techniques. These methods are often employed in various types of industries, including pharmaceuticals, food safety and environmental monitoring for separation and analysis of complex mixtures.However, due to their toxicity, lack of biodegradability, and pollution, the traditional use of volatile organic solvents (VOCs) in these processes pose serious risk to environment and human health. Green solvents, or solvents that improve environment and human health, are becoming more and more popular as a solution to these problems, preserving analytical performances. Green solvents such as ionic liquids (IL_S), supercritical carbon dioxide, bio-based solvents, and deep eutectic solvents (**DESs**) are offered to low poisoning, biodegradability and renewal sourcing. This research examines his application in chromatographic techniques, aimed at evaluating overall effectiveness as an alternative to their separation efficiency, environmental stability and traditional solvents. In terms of chromatography, a green solvent is usually defined by several criteria, each of which helps reduce the environmental and health effects of chromatographic methods:

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- Low toxicity: Green solvents should be non -toxic for both environment and human health. If it enters the environment, the solvent should not have significant health risk to laboratory personnel or public. Low toxicity also ensures that it is safe for use in sensitive areas such as drug testing and food analysis.
- Biodegradation: A major feature of green solvents is that they will have to break into non -toxic, naturally occurring substances when issued in the environment. This guarantees that there are no dull solvents in the environment and reduce long -term ecological losses.
- Renewal: Ideally, green solvents come from renewable sources such as biomass, plant or agricultural waste. Solutions obtained from renewable resources, such as ethanol, limonene, or some bio-based ionic fluids, can be produced, reducing dependence on chemicals obtained from petroleum.
- Low environmental effects: Beyond poisoning and biodegradability, carbon footprints of green solvents, water use and production, use and disposal should have minimal environmental effects in terms of energy consumption during and disposal.
- Effectiveness in chromatography: While environmental and safety ideas are most important, a green solvent should also show good chromatographic performance. It should effectively dissolve a wide range of solutions, support high resolution and selectivity in isolation, and ensure reproducible, sensitive analytical results.
- •Low instability: Volatile solvents, especially volatile organic compounds (VOCs), are a major contributor to air pollution, resulting in smog and other environmental problems. The best green solvents are low vapour to reduce pressure emissions and establish a safe laboratory environment.
- Distinguish from current systems: A green solvent requires working with supplies and equipment used in chromatographic processes including detectors, columns and other equipment. The practical application of a solvent can be limited if it is inconsistent as it can cause expensive tool failure or decline.

Importance of green solvent selection in chromatography:

In chromatography, the choice of solvents is important for both the overall stability and the effectiveness and resolution of separations. Although they work well for chromatographic separation, traditional solvents such as acetonitrile, methanol and hexane have significant drawbacks and environmental issues. The use of such solvents produces large amounts of chemical waste, contributes to air and water pollution, and requires stringent disposal processes, often increases the cost for laboratories and industries. Green solvents provide the possibility of reducing many of these concerns. Labs can support a circular economy, which reduces waste and reuse content using solvents with minimal environmental impact and low toxicity. In addition, these solvents often show the same or better chromatographic separation performance, making them a possible option for high-extending analysis. The change of green solvents is aligned with both regulator and corporate stability goals. Regulatory agencies, such as U.S. EPA and European Union access rules, safety in all chemical processes, including analytical techniques, are emphasizing the need for greener practices. Companies and institutions that adopt greener solvent systems not only ensure compliance with these rules, but also keep themselves in position as leaders in corporate social responsibility (CSR), which addresses the increasing demand for sustainable and environment friendly practices.

Chromatography includes green solvents such as ionic fluid (IL_S), supercritical fluid (SCFS), deep eutectic solvents, and bio-based solvents. ILS LC, GC and SFC are low-stimulated salts offering excellent stability, but suffer from high viscosity and cost. SCFs, especially supercritical fluids, enable rapid isolation in SFC, but require high pressure systems and require conflicts with polar compounds.

Challenges in Green Solvent Selection for Chromatography

While the benefits of green solvents are clear, their widespread adoption in chromatography leads to a group of challenges. One of the primary obstacles is the cost associated with several green solvents. Bio-based solvents, while durable, are often more expensive to produce conventional petrochemical-derived solvents. This economic idea can obstruct transition, especially in industries where cost efficiency is most important.

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Another challenge is the compatibility of green solvents with existing chromatographic systems. Some green solvents, such as ionic fluids or supercritical fluids, may require special equipment or adjustment, for standard methods, increase early investment for laboratories. In addition, the lack of extensive databases on green solvent properties and their interaction with various analyses and materials complicate the adaptation of chromatographic methods.

Further research is also required in scalability of green solvents for industrial applications. While many green solvents show promising consequences in the study on laboratory-fame, their performance in large-scale production processes, such as pharmaceutical manufacturing or environmental supervision, requires further investigation.

Types of Green Solvents in Chromatography

According to the ideas of green chemistry, green solvents are used in chromatography in place of traditional harmful solvents. The ionic fluid (ILS), supercritical fluid (SCFS), deep gestational solvents, and bio-based solvents are primary categories, and provides special benefits in terms of each performance and environment.

- **Ionic Liquids (ILs)**: There are ionic fluid salts that remain liquid at room temperature. They have low vapour pressure, high thermal and chemical stability and adaptable properties, making them effective in dissolving both polar and non-polar compounds. IL is applied to liquid, gas and supercritical fluid chromatography. However, they may have high viscosity and cost boundaries.
- **Supercritical Fluids (SCFs):** Supercritical fluid (SCFS), especially supercritical carbon dioxide ($scco_2$), combine gas-like diffusivity with liquid-like solvating power. They are non-toxic, low in environmental effects, and suitable for supercritical fluid chromatography (SFC) and extraction techniques. Their major drawbacks require high pressure devices and limited solubility for polar analysis.
- **Deep Eutectic Solvents (DESs)**: Deep eutectic solvents (DES) are formed by combining hydrogen bond donors and acceptors, often from natural sources. They are biodegradable, low-cost, and provide adaptable properties for liquid and thin layer chromatography. Challenges include high viscosity and limited solubility for some analyses.
- **Bio-based Solvents**: Bio-based solvents are obtained from renewable sources such as corn, sugarcane and sour peels. They are low in poisoning, biodegradable and durable. It's used in liquid chromatography and sample preparation. They reduce environmental effects, but face issues with solvent compatibility, availability and cost.

II. LITERATURE REVIEW

1. Green solvents in liquid chromatography (LC)

Liquid chromatography (LC) is one of the most widely used techniques in analytical chemistry. Traditional mobile stages such as methanol and acetonitrile are toxic and environmentally harmful. The ionic fluid (ILS) has attracted significant attention in the form of alternative solvents due to their low instability, high thermal stability and tuneable properties. Studies have shown that IL, especially with hydrophobic ions, improve the separation efficiency for polar analyses and enhance the resolution in reversal--LC (Burton et al., 2017). Bio-based solvents such as ethyl lactate and limonene have also been detected, offering the same performance as traditional solvents, while biodegradables and are obtained from renewable resources (Lopez et al., 2019).

2. Green solvents in gas chromatography (GC)

In gas chromatography (GC), the use of ionic fluid (ILS) as stable stages has been shown to improve separation efficiency and column longevity due to their thermal stability and low volatility (Zhou et al., 2019). Another successful mobile phase is supercritical carbon dioxide ($scco_2$), which provides benefits including slightly solvent waste, energy efficiency and low poisoning (RIOS et al., 2015). $SCCO_2$, still encounters difficulties in GC applications, yet, due to its poor solubility and high pressure needs for polar molecules.

3. Supercritical fluid chromatography using green solvents (SFC)

For non-polar and semi-polar substances, supercritical fluid chromatography (SFC) has been accepted as a viable option for traditional LC. It has been displayed that using $scco_2$ as a mobile phase in SFC provides exceptional separation efficiency with low solvent waste and further analytical time's further benefits. To increase the solubility of polar

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substances, co-students such as ethanol are usually employed (Kumar et al., 2016). In addition, as an addition of $scco_2$, deep eutectic solvents (des) have been examined; They offer low poisoning, biodegradability and better separation efficiency (Perera et al., 2020).

4. Green solvents in thin-layer chromatography (TLC)

Thin-layer is benefited by the use of bio-based solvents such as chromatography (TLC), a simple chromatographic method, ethyl lactate and limonene as mobile stages. These solvents offer comparable performance for traditional organic solvents such as benzene and chloroforms, but with low toxicity and high biodegradable (rios et al., 2018). Deep eutectic solvents (DES) are also being detected in TLC for separation of bioactive compounds and natural products; however, their high viscosity may obstruct migration and separation efficiency.

III. RESULTS AND DISCUSSIONS

1. Performance of green solvents in liquid chromatography (LC)

The use of ionic fluids (ILS) and bio-based solvents (ethyl lactate,, limonene) as mobile phase in LC performed comparable or better in terms of separation efficiency compared to traditional solvents such as methanol and acetonitrile. In particular, ILS with hydrophobic anions demonstrated better separation for polar analyses, although their high viscosity extended the backpressure, which could limit their practical use in the high throughput system. Bio-based solvents, especially the ethyl lactate, offered equal retention time and resolution, but were noted for their low toxicity and high biodegradability.

2. Performance in Gas Chromatography (GC)

In GC, ILs used as stable stages resulted in better separation efficiency and prolonged column life than traditional organic stationary phases. As a mobile phase, supercritical carbon dioxide ($SCCO_2$) provided efficient segregation of non-polar compounds, especially when combined with small amounts of co-solvents such as ethanol. The time of separation was reduced compared to traditional organic solvents, and environmental effects were quite low. However, pressure requirements for supercritical carbon dioxide remained a challenge for mass applications.

3. Supercritical fluid chromatography (SFC) results

Supercritical carbon dioxide ($SCCO_2$) combined with a small percentage of ethanol, was highly effective in separating non-polar and semi-polar compounds in SFC. The lower solvent waste and rapid analysis were the major benefits, and the results showed high resolution with minimal environmental impacts. However, the solubility of polar compounds remained limited until further adaptation of the co-solvent was applied. DES**s** as additives in $SCCO_2$-based SFCs showed promising results for drug and environmental analysis, although issues related to co-solvent interaction and pressure stability require further investigation.

4. Thin-layer chromatography (TLC) results

In TLC, green solvents such as ethyl lactate and limonene provided excellent separation for bioactive compounds with RF values similar to traditional solvents such as benzene and chloroforms. These solvents, being biodegradable, reduced the environmental impact of the process. However**,** DESs in TLC, shows a slow migration due to its high viscosity, which in some cases could affect the resolution.

5. Environment and stability evaluation

Life-cycle analysis (LCA) of Green Solvents said that IL_S and $scco_2$ provides significant environmental benefits in terms of low poisoning, biodegradability and minimum solvent waste. Bio-based solvents, especially ethyl lactate, performed the best overall stability due to their renewable original, low toxic effects and easy disposal. However, the cost idea was a limit for large -scale industrial use of some of these green solvents.

IV. CONCLUSION

This study suggests that green solvents can be used as a practical, environment friendly alternative to traditional organic solvents in chromatographic processes. In chromatography, ionic fluid (IL_S) and supercritical carbon dioxide ($SCCO_2$) showed strong performance, reduced environmental impact and separated isolation efficiency. Bio-based solvents, such as ethyl lactate, were beneficial due to their renewable nature and biodegradability, making them a strong contender for changing toxic solvents in various chromatographic applications. Despite these promising results, challenges remain,

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including viscosity issues with some green solvents (e.g. IL_S and des) and some cost factors. Further adaptation of solvent properties, including better co-solvent systems and cost-effective production methods, is required to adopt green solvents in chromatography widely. Finally, while green solvents in chromatography have great ability to increase stability in analytical processes, further research requires further research to resolve technical and economic challenges to ensure their practical implementation.

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