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LIFECYCLE ASSESSMENT OF GREEN ANALYTICAL METHODS: A COMPREHENSIVE REVIEW

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Abstract: In the quest for sustainable and environmentally friendly practices, the field of analytical chemistry has witnessed a growing interest in the development of green analytical methods. These methods aim to minimize the environmental impact of analytical processes throughout their lifecycle, encompassing raw material extraction, method development, analysis, waste generation, and disposal. This review article provides a comprehensive analysis of the key principles, and methodologies related to the lifecycle assessment (LCA) of green analytical methods.

Index Terms **- Green analytical methods, lifecycle assessment, environmental sustainability, analytical chemistry, green chemistry, eco-friendly, method development.**

I. INTRODUCTION

In the quest for a more sustainable and environmentally conscious world, the field of analytical chemistry has been undergoing a paradigm shift towards the adoption of greener practices. Analytical methods play a pivotal role in various industries, ranging from pharmaceuticals and food safety to environmental monitoring (Ciroth, (2011)). However, many conventional analytical techniques are associated with significant environmental impacts, including the generation of hazardous waste, energy consumption, and emissions of volatile organic compounds. This has prompted researchers and industries to explore and develop greener alternatives that minimize the ecological footprint of analytical processes.

The concept of Green Analytical Chemistry (GAC) has gained traction as a framework for developing environmentally friendly analytical methods (Anastas, 1998). One of the key components of GAC is the implementation of Lifecycle Assessment (LCA) principles, which offer a holistic perspective on the environmental impacts of a method from cradle to grave (Arvidsson, (2011)). LCA considers various stages of an analytical method's lifecycle, including raw material extraction, production, operation, and disposal, and assesses their cumulative environmental effects (Curran, (2013)).

II. IMPORTANCE OF THE STUDY

This research paper aims to delve into the emerging field of Green Analytical Chemistry and its integration with Lifecycle Assessment methodologies (Hitzel, 2016). By evaluating and comparing the environmental performance of both traditional and green analytical methods, this study intends to provide a comprehensive understanding of the benefits and challenges associated with adopting greener practices in chemical analysis.

The significance of this research lies in its potential to guide analytical chemists, researchers, and industries toward more sustainable choices when selecting analytical techniques (Namieśnik, (2014)). As concerns about climate change, resource depletion, and pollution continue to grow, there is a pressing need to identify and promote methods that reduce the environmental impact of chemical analysis without compromising analytical performance (Kantiani, 2009).

III. GREEN ANALYTICAL CHEMISTRY

"Green analytical principles" generally refer to a set of guidelines and practices that promote environmentally friendly and sustainable approaches in analytical chemistry. Analytical chemistry is the branch of chemistry that deals with the identification and quantification of substances and compounds in various samples (Agnieszka Gałuszka, 2013). Green analytical principles aim to minimize the environmental impact of analytical processes while maintaining the accuracy and reliability of the results (Richter, 1998). Here are some key principles associated with green analytical chemistry:

1. Minimization of Hazardous Substances: Use of fewer hazardous chemicals and reagents in analytical procedures, reducing the generation of toxic waste and the potential for environmental harm.
2. Waste Minimization: Designing methods that produce less waste, promoting recycling and reusability of materials whenever possible.

3. Use of Renewable Resources: Utilizing renewable resources, such as green solvents derived from natural sources, instead of traditional, non-renewable solvents.
4. Safer Reagents and Solvents: Opting for reagents and solvents that are less harmful to human health and the environment, without compromising analytical accuracy.
5. Miniaturization and Micro techniques: Employing microscale and miniaturized analytical techniques that require smaller samples, reagents, and energy inputs.
6. Green Instrumentation: Designing and using analytical instruments that are energy-efficient, consume fewer resources, and produce less waste.
7. Automation and High-Throughput Analysis: Implementing automation and robotics to improve efficiency, reduce human error, and decrease the amount of reagents and materials used.
8. Lifecycle Assessment: Considering the entire lifecycle of analytical methods, from sample collection to disposal, to identify opportunities for reducing environmental impact.
9. Alternative Techniques: Exploring alternative analytical techniques that have lower environmental impact, such as spectroscopic methods that don't require extensive sample preparation.
10. Green Sample Preparation: Developing sample preparation methods that require fewer reagents and less energy, reducing the overall environmental footprint.
11. Collaboration and Knowledge Sharing: Sharing information and collaborating across the scientific community to collectively develop and adopt greener analytical practices.
12. Education and Training: Educating scientists, researchers, and students about green analytical principles to promote their incorporation into research and laboratory practices.

By following these green analytical principles, researchers and laboratories can contribute to more sustainable and eco-friendly approaches in analytical chemistry, minimizing the environmental impact of their work while still achieving accurate and reliable results (Namieśnik, (2014)), (M. de la Guardia and S. Garrigues, 2020), (S. Armenta, 2008)

IV. LIFECYCLE ASSESSMENT OF ANALYTICAL METHODS

Lifecycle Assessment (LCA) is a systematic approach used in green chemistry to evaluate the environmental impacts of a product, process, or activity throughout its entire lifecycle (Huijbregts, 2016), (Suh, 2005). This assessment provides insights into the potential environmental benefits and drawbacks of various alternatives and helps guide decision-making towards more sustainable options (ISO 14040: Environmental management - Life cycle assessment - Principles and framework.), (ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines.). Here are the steps of the Lifecycle Assessment in detail:

1. Goal and Scope Definition: This initial step involves defining the purpose and boundaries of the LCA study. The goal specifies what is being assessed (e.g., a product, process, or system), while the scope outlines the functional unit (the quantifiable measure of the product/process performance) and system boundaries (the stages of the lifecycle to be considered). Clear definition ensures consistency and comparability of results.
2. Inventory Analysis: In this phase, a detailed inventory of all relevant inputs and outputs associated with the product or process is compiled. This includes raw materials, energy sources, emissions, waste, and other resources used throughout the lifecycle. The data gathered here serve as the basis for subsequent assessments.
3. Life Cycle Impact Assessment (LCIA): LCIA involves evaluating the potential environmental impacts associated with the inputs and outputs identified in the inventory analysis. This step typically involves categorizing impacts into different impact categories such as global warming, acidification, eutrophication, human toxicity, etc. LCIA uses various impact assessment methods, such as life cycle midpoint and endpoint approaches, to quantify these potential impacts.
4. Interpretation: Interpretation involves analysing the results of the impact assessment in the context of the study's goals and scope. This step aims to identify significant impacts, key contributors, and areas of improvement. It helps stakeholders understand the environmental implications and prioritize actions for mitigation.
5. Normalization and Weighting (optional): In some cases, LCA studies normalize and weight impact scores to provide a more concise and easily interpretable summary of the results. Normalization scales the impact scores relative to a reference situation, while weighting assigns relative importance to different impact categories based on societal or stakeholder values.
6. Improvement Assessment: Building upon the interpretation phase, this step involves exploring opportunities for reducing the identified environmental impacts. Different alternatives and strategies are assessed to determine which actions could lead to more sustainable outcomes. This step often requires collaboration between researchers, engineers, and decision-makers.
7. Reporting: The findings of the LCA study are compiled into a comprehensive report that includes all relevant information, assumptions, methodologies, results, and conclusions. Transparency is crucial to ensure that stakeholders understand the basis for the assessment and its implications.
8. Review and Validation: The LCA study should undergo a review and validation process to ensure the accuracy, consistency, and reliability of the methodology and results. This step might involve peer review, expert consultation, or independent verification.
9. Decision-Making: The final LCA results and recommendations are used by stakeholders to make informed decisions. This could involve selecting a more sustainable product design, altering a process, or choosing between different alternatives based on their environmental performance.
10. Iterative Process: LCA is often an iterative process, as improvements and innovations are continuously developed. As new data, technologies, and methodologies emerge, LCA studies can be updated to reflect the changing landscape of sustainability.

By following these steps, green chemists and sustainability professionals can effectively evaluate and compare the environmental performance of different options, guiding the development of more environmentally friendly products and processes (Kappei, 2017), (Yang, 2014) .

4.1 Advantages

LCA considers the entire lifecycle, including raw material acquisition, production, use, and disposal. This holistic view helps identify environmental impacts that might be overlooked when focusing only on a specific phase of the lifecycle. LCA provides data-driven insights that help in making informed decisions about the most environmentally friendly methods. This is especially important in the context of green methods, where the goal is to minimize environmental harm. LCA allows for the comparison of different green methods or technologies. It helps in identifying which method has the least environmental impact, enabling the selection of the most sustainable option. LCA identifies the key stages of the lifecycle that contribute the most to environmental impacts. This allows for targeted efforts to reduce these impacts, leading to more effective improvements. LCA can assist policymakers and regulators in setting standards and regulations that encourage the adoption of green methods. It provides a scientific basis for environmental policies. LCA results can be communicated to stakeholders, such as consumers, investors, and communities, to demonstrate the environmental benefits of using green methods. This transparency can enhance trust and reputation.

4.2 Drawbacks

Conducting a comprehensive LCA requires a substantial amount of data and expertise. It can be time-consuming and resource-intensive, which might not be feasible for all projects or organizations. LCA relies on accurate and up-to-date data for all stages of the lifecycle. Data gaps and uncertainties can impact the reliability of results and comparisons. Some aspects of LCA, such as selecting impact categories and assigning weights to different impacts, involve subjective judgments. This subjectivity can influence the final results. Defining the scope and boundaries of the assessment can be challenging. Different choices can lead to different results, making comparisons less straightforward. LCA primarily focuses on environmental impacts and might not consider other important aspects like social or economic factors. This could lead to a narrow perspective on sustainability. LCA assumes a relatively static system, but real-world systems are dynamic and subject to changes. Technological advancements or shifts in market conditions can influence the accuracy of LCA results over time. LCA heavily relies on quantifiable data, which might not capture all relevant environmental or social aspects, potentially leading to an oversimplification of complex issues.

In conclusion, while Lifecycle Assessment offers a valuable framework for evaluating the environmental impacts of green methods, its application involves both advantages and drawbacks. Careful consideration of these factors is essential to ensure meaningful and actionable results that contribute to sustainable decision-making.

V. GREEN ANALYTICAL SOLVENTS:

Green analytical solvents, also known as environmentally friendly solvents or sustainable solvents, are a class of solvents that are designed to minimize their environmental impact while still being effective for various analytical applications. Traditional solvents used in analytical chemistry, such as chlorinated solvents and volatile organic compounds (VOCs), can have negative effects on human health and the environment due to their toxicity, volatility, and potential to contribute to air pollution. (Dhir, 2018)
Green analytical solvents aim to address these issues by possessing characteristics such as:

1. Low Environmental Impact: Green solvents are chosen based on their lower potential to harm the environment, such as reduced toxicity and lower levels of hazardous air pollutants.
2. Renewable and Sustainable Sources: These solvents are often derived from renewable resources, such as agricultural products, biomass, or waste streams from other processes, reducing the reliance on fossil fuels.
3. Biodegradability: Green solvents are designed to break down into non-harmful compounds through natural processes, reducing their persistence in the environment.
4. Low VOC Emissions: Volatile Organic Compounds (VOCs) contribute to air pollution and can have adverse health effects. Green solvents typically have lower VOC emissions.
5. Energy Efficiency: The production and use of green solvents often require less energy compared to traditional solvents.
6. Compatibility with Analytical Techniques: Green solvents need to be suitable for various analytical methods, including spectroscopy, chromatography, and sample preparation.

Examples of green analytical solvents include:

1. Ionic Liquids: These are salts that remain in the liquid state at room temperature. They have low volatility, and low toxicity, and can be derived from renewable sources.
2. Supercritical Carbon Dioxide (SC-CO_2): Carbon dioxide in a supercritical state can replace traditional organic solvents for certain applications. It is non-toxic, non-flammable, and can be easily removed from the sample.
3. Deep Eutectic Solvents (DES): These are mixtures of two or more compounds that when combined, form a liquid at a lower temperature than either of the individual components. They can be derived from natural compounds and have low toxicity.
4. Water: Water is considered the most environmentally friendly solvent and can be used for a wide range of applications, especially when coupled with appropriate methods and additives.
5. Biomass-Derived Solvents: Solvents derived from renewable biomass sources, such as ethanol from agricultural residues, can be used for certain applications.

The development and utilization of green analytical solvents contribute to more sustainable and environmentally conscious practices in analytical chemistry, minimizing the negative impact on both human health and the planet.

5.1 Ionic liquids

Ionic liquids are a type of salt that exists in a liquid state at or around room temperature. They have unique properties that make them useful in various applications, including in High-Performance Liquid Chromatography (HPLC) analysis (Earle, 2000). Ionic liquids can be used as a replacement for traditional organic solvents as mobile phases in HPLC, offering advantages like improved separation and selectivity (Shimizu, 2006), (Han D, 2010). Here are some examples and uses of ionic liquids in HPLC analysis:

Examples of Ionic Liquids:

1. 1-Butyl-3-methylimidazolium chloride (BMIM Cl): This is one of the most commonly used ionic liquids in HPLC analysis. It has been employed as an additive in the mobile phase to enhance selectivity and retention of analytes.
2. 1-Octyl-3-methylimidazolium tetrafluoroborate (OMIM BF4): This ionic liquid has been used to modify the selectivity and retention of analytes in HPLC separations.
3. 1-Ethyl-3-methylimidazolium acetate (EMIM Ac): It has been utilized in HPLC separations, especially for the analysis of organic acids and other polar compounds.

Uses in HPLC Analysis:

1. Improved Selectivity: Ionic liquids can alter the separation selectivity in HPLC. By choosing an appropriate ionic liquid as a mobile phase additive, you can achieve better separation of closely related compounds.
2. Enhanced Retention: Ionic liquids can increase the retention time of specific analytes, leading to better separation and sharper peaks. This can be advantageous in cases where analytes are difficult to separate using traditional mobile phases.
3. Analysis of Polar Compounds: Ionic liquids can be particularly useful for the analysis of polar and hydrophilic compounds that might not be well retained using conventional organic solvents. They can provide better peak shapes and improved chromatographic performance for such compounds.
4. Chiral Separations: Some ionic liquids have been shown to enhance the enantioselectivity in chiral separations, enabling the separation of enantiomers that are challenging to resolve using other mobile phases.
5. Green Analytical Chemistry: Ionic liquids are often considered "greener" alternatives to traditional organic solvents due to their lower volatility and reduced environmental impact. Using ionic liquids in HPLC can contribute to more environmentally friendly analytical practices.
6. Sample Preparation: Ionic liquids can also be used in sample preparation techniques before HPLC analysis, aiding in the extraction, preconcentration, and cleanup of analytes from complex matrices.

It's important to note that the selection of an appropriate ionic liquid depends on the specific analytes, the stationary phase, and the separation objectives (Canals, 2019) . Additionally, some challenges associated with using ionic liquids in HPLC include potential column and equipment compatibility issues, as well as limited availability of certain ionic liquids (Anderson, 2010) (Ragonese, 2013), (Gou, 2015).

5.2 Supercritical carbon dioxide (SC-CO2)

Supercritical carbon dioxide (SC-CO2) is a state of carbon dioxide where it is maintained at a temperature and pressure above its critical point (King, 1984). In this state, CO2 exhibits properties of both a gas and a liquid, making it a unique solvent for various applications, including high-performance liquid chromatography (HPLC) analysis (Peters, 2012). SC-CO2 is often used as an alternative mobile phase solvent in HPLC due to its favourable characteristics, such as low viscosity, high diffusivity, and tunable solvent strength (Ramdin, 2017).

Here are a few examples of how SC-CO2 can be utilized in HPLC analysis:

1. Separation of Complex Mixtures: SC-CO2 can be used as a mobile phase to separate complex mixtures of compounds. Its low viscosity allows for efficient chromatographic separations, and its tunable solvent strength can help in optimizing the separation of compounds with varying polarities (Reverchon, 2006).
2. Natural Products Analysis: SC-CO2 is often employed for the analysis of natural products, such as plant extracts (Brunner, 2009). It can selectively extract compounds of interest from these matrices, and then the extracted compounds can be analyzed using HPLC for quantification and identification (Subramaniam, 2013).
3. Chiral Separations: Chiral compounds are molecules that exist in mirror-image forms (enantiomers), and their separation is important in pharmaceutical and chemical industries. SC-CO2-based chiral chromatography can offer improved selectivity and efficiency in separating enantiomers.
4. Environmental Analysis: SC-CO2 can be used for the extraction of environmental contaminants from solid samples, such as soil and sediment. The extracted analytes can then be analyzed using HPLC to quantify pollutants like pesticides, polycyclic aromatic hydrocarbons (PAHs), and more.
5. Food and Beverage Analysis: SC-CO2 can be utilized to extract flavor compounds, additives, and contaminants from food and beverage samples. These extracted compounds can be subsequently analyzed using HPLC to ensure food safety and quality (Vinatoru, 2001).
6. Pharmaceutical Analysis: SC-CO2 can be employed in the analysis of pharmaceutical products, such as drug formulations and dosage forms. It can be used for sample preparation, extraction of active pharmaceutical ingredients, and impurity profiling.
7. Polymer Analysis: SC-CO2 can assist in the analysis of polymers by extracting low-molecular-weight components from polymer matrices. The extracted components can then be characterized using HPLC.
8. Supercritical Fluid Chromatography (SFC): SFC is a chromatographic technique that utilizes SC-CO2 as the primary mobile phase. It offers fast separations and can be coupled with various detectors, including UV, mass spectrometry, and refractive index detectors.

It's important to note that while SC-CO2 offers several advantages, it also has limitations, such as limited solubility for highly polar compounds and challenges in detector compatibility (Lee, 2003). The choice to use SC-CO2 in HPLC analysis depends on the specific requirements of the analysis and the types of compounds being studied (Polaert, 2014).

5.3 Deep Eutectic Solvents (DES)

Deep Eutectic Solvents (DES) have gained attention as alternative solvents in various chemical processes, including analytical techniques like High-Performance Liquid Chromatography (HPLC) (Liu, 2021) (Smith, 2014). DES is a type of ionic liquid formed by mixing a hydrogen bond donor and a hydrogen bond acceptor, resulting in a eutectic mixture with unique properties that can be tailored for specific applications (Dai Y, 2013), (Abbott AP, 2004). In HPLC, DES can serve as environmentally friendly and efficient mobile phase solvents (Zhang Q, 2012). A few examples of DES used in HPLC analysis:

1. Choline chloride-urea: This is one of the most well-known and widely used DES in HPLC analysis (Smith EL, 2014). It consists of choline chloride (hydrogen bond acceptor) and urea (hydrogen bond donor). This DES has been employed in the separation of various compounds, such as amino acids, flavonoids, and pharmaceuticals.
2. Choline chloride-malonic acid: This DES is composed of choline chloride and malonic acid. It has been applied in HPLC for the separation of compounds like polyphenols, organic acids, and basic drugs.
3. Choline chloride-glycerol: This DES, formed by mixing choline chloride and glycerol, has been utilized in HPLC to separate various analytes, including phenolic compounds, flavonoids, and organic acids.
4. Choline chloride-acetic acid: Comprising choline chloride and acetic acid, this DES has been employed in HPLC analysis for the separation of compounds like nucleosides and nucleobases.
5. Urea-based DES: Various DES can be prepared using urea as a common hydrogen bond donor, along with different hydrogen bond acceptors. These DES can be tailored to suit specific separation requirements in HPLC analysis.
6. Lactic acid-based DES: DES containing lactic acid as one of the components have been used in HPLC to separate organic acids, flavonoids, and other bioactive compounds.

It's important to note that the choice of DES for HPLC analysis depends on the specific properties of the analytes to be separated, as well as the desired separation conditions. While DES offer certain advantages such as low toxicity, tunable polarity, and environmentally friendly characteristics, they might also present challenges related to compatibility with HPLC systems and potential interference with detection methods.

As research in the field of DES continues, more innovative combinations and applications for HPLC analysis are likely to emerge, expanding the possibilities for efficient and sustainable separation techniques.

5.4 Water

High-Performance Liquid Chromatography (HPLC) is a widely used analytical technique in chemistry to separate, identify, and quantify components in a mixture (Clark, 2015). Water is a critical component in HPLC analysis, serving various purposes throughout the process (Sheldon, 2007). Here are some examples of its use:

1. Mobile Phase Preparation: Water is often used as a component of the mobile phase, which is the liquid that carries the sample through the chromatography system. In many cases, the mobile phase is a mixture of water and other solvents (such as acetonitrile or methanol) in varying proportions. The choice of solvent composition affects the separation of compounds based on their polarity.
2. Buffer Solution Preparation: If ionizable compounds are being analyzed, a buffer solution containing water is used to maintain a constant pH of the mobile phase. Buffer solutions help to control the ionization of analytes, which can impact their retention times and separation on the column.
3. Sample Dilution: Before injection into the HPLC system, samples are often diluted to appropriate concentrations. Water is a common solvent for dilution, especially for samples that are water-soluble or can be dissolved in aqueous solutions.
4. Column Conditioning: HPLC columns, which are packed with stationary phase material, need to be equilibrated and conditioned before use. Water can be used as part of the initial conditioning process to prepare the column for proper separation.
5. Column Washing: After each analysis, the column might need to be washed to remove any residual compounds from the previous run. Water can be used as a wash solvent to clean the column before running the next sample.
6. Pre-column Filters and Guards: Water is used to flush and clean pre-column filters and guard columns, which are placed before the main analytical column. These components protect the main column from particulates and contaminants that could interfere with the analysis.
7. Sample Solvent: Water can be used as a solvent to prepare standard solutions and calibration curves for quantitative analysis. This is especially true for compounds that are stable and soluble in aqueous solutions.
8. Gradient Elution: In gradient elution, the composition of the mobile phase changes over time. Water is often used as a component in the initial, less polar portion of the gradient, gradually transitioning to more organic solvents as the separation progresses.

It's important to note that the choice of water quality, such as distilled, deionized, or ultrapure water, depends on the sensitivity of the analysis and the potential for impurities to interfere with the results (Tundo, 2007). Water quality is especially crucial when dealing with trace-level analyses or when using detectors sensitive to contaminants.

5.5 Biomass-derived solvents

Biomass-derived solvents are environmentally friendly alternatives to traditional organic solvents that are derived from fossil fuels. These solvents are sourced from renewable biomass feedstocks and can be used in various applications, including HPLC analysis (Zhao, 2017). Some examples of solvents that can be used in HPLC:

1. Ethanol: Ethanol is a common biomass-derived solvent obtained from the fermentation of sugars present in biomass feedstocks like corn, sugarcane, and cellulosic materials. It can be used as a mobile phase solvent in HPLC analysis.
2. Isopropanol (Isopropyl alcohol): Isopropanol can be derived from biomass sources like corn or sugarcane. It's used as a solvent in HPLC, especially in the analysis of compounds sensitive to water.
3. Acetonitrile (ACN) from Bio-based Sources: Acetonitrile is a common HPLC solvent, and efforts have been made to develop bio-based routes to produce it from renewable feedstocks like biomass. Various methods, such as fermentation of sugars, have been explored to produce bio-based acetonitrile.
4. Dimethyl sulfoxide (DMSO) from Biomass: DMSO can be produced from lignocellulosic biomass sources and has applications as a solvent in HPLC, particularly for analyzing complex samples.
5. Glycerol: Glycerol is a byproduct of biodiesel production and can be sourced from animal fats or plant oils. It can be used in HPLC as a solvent for specific applications.
6. Formic Acid from Biomass: Formic acid is used as an additive in the mobile phase for some HPLC analyses. It can be produced from biomass-derived sources, contributing to sustainability.
7. Lactic Acid-Derived Solvents: Lactic acid, obtained from fermentation of biomass sugars, can be used as a precursor to produce various solvents that are potentially useful in HPLC applications.
8. Terpenes: Terpenes are natural compounds found in plants and can be extracted from biomass. They have been explored as alternative solvents for various applications, including HPLC (Sheridan, 2016).

The compatibility of these biomass-derived solvents with HPLC systems, columns, and detectors might vary. Parameters such as viscosity, UV absorbance, and solvent purity should be considered when selecting and using these solvents in HPLC analysis. Additionally, advances in green chemistry and sustainable technologies continue to expand the range of available biomass-derived solvents for analytical techniques like HPLC.

VI. CONCLUSION:

Conducting a lifecycle assessment (LCA) of green analytical methods with an emphasis on the solvents used is essential to comprehensively evaluate the environmental impact of these techniques. Green analytical methods aim to minimize their ecological footprint by adopting sustainable practices throughout their lifecycle, from raw material extraction to disposal. The choice of solvents plays a crucial role in determining the overall environmental performance of these methods.

Through the LCA process, it becomes evident that the selection of environmentally benign solvents is a key factor in reducing the carbon footprint and minimizing toxicity associated with analytical procedures. Green solvents, such as water, supercritical fluids, and bio-based alternatives, offer distinct advantages over traditional volatile organic solvents in terms of reduced emissions, lower energy consumption, and safer disposal. Their use can significantly lower the overall environmental impact of analytical methods, contributing to more sustainable laboratory practices.

VII. REFERENCES

1. Abbott AP, B. D. (2004). Deep eutectic solvents formed between choline chloride and carboxylic acids: versatile alternatives to ionic liquids. *J Am Chem Soc.*
2. Agnieszka Gałuszka, Z. M. (2013). The 12 principles of green analytical chemistry and the SIGNIFICANCE mnemonic of green analytical practices. *TrAC Trends in Analytical Chemistry, Volume 50*, 78-84.
3. Anastas, P. T. (1998). *Green Chemistry: Theory and Practice. Oxford University Press.* Oxford University Press.
4. Anderson, J. L. (2010). Using Ionic Liquids to Stabilize Late Transition Metal Nanoparticles. *Journal of the American Chemical Society*, 3228-3229.
5. Arvidsson, R. B. ((2011)). The role of life cycle assessment in supporting sustainable supply chain and materials management. . *The International Journal of Life Cycle Assessment, 16(4)*, 379-389.
6. Brunner, G. (2009). Supercritical Fluids: Technology and Application to Food Processing. *Journal of Food Engineering*, 21-33.
7. Canals, A. B. (2019). Ionic Liquids as Stationary Phases in High-Performance Liquid Chromatography: A Review. *Analytica Chimica Acta*, 29-45.
8. Ciroth, A. &. ((2011)). *Life cycle assessment of analytical procedures: comparing one technologically mature method with a new advanced technology. Green Chemistry, 13(11), 3177-3185.* Royal Society of Chemistry.
9. Clark, J. H. (2015). *Alternative solvents for green chemistry.* . RSC Publishing.
10. Curran, M. A. ((2013)). *Life cycle assessment handbook: A guide for environmentally sustainable products.* CRC Press.
11. Dai Y, v. S. (2013). Natural deep eutectic solvents as new potential media for green technology. . *Anal Chim Acta.* .
12. Dhir, S. &. (2018). Application of Green Analytical Techniques in the Environmental Field. *Current Analytical Chemistry, 14(4)*, 440-454.
13. Earle, M. J. (2000). Ionic liquids. Green solvents for the future. *Pure and Applied Chemistry*, *72(7)*, 1391-1398.
14. Gou, H. W. (2015). Recent Advances in Ionic Liquid Stationary Phases and Analytical Applications in High-Performance Liquid Chromatography. *Journal of Separation Science*, 20-42.
15. Han D, R. K. (2010). Recent applications of ionic liquids in separation technology. *Molecules*.
16. Hitzel, S. M. (2016). Green Analytical Chemistry. *Analytical Chemistry, 88(2),*, 1026-1031.

17. Huijbregts, M. A. (2016). *Life cycle assessment.* Springer.
18. ISO 14040: Environmental management - Life cycle assessment - Principles and framework. (n.d.).
19. ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines. (n.d.).
20. Kantiani, L. &. (2009). Analytical methodologies for the detection of photochemical transformation products of emerging pollutants in the aquatic environment. *TrAC Trends in Analytical Chemistry, 28(6)*, 676-684.
21. Kappei, L. &. (2017). 100% Green analytical chemistry. *Analytical and Bioanalytical Chemistry, 409(21)*, 4843-4848.
22. King, J. W. (1984). Supercritical fluid extraction . *Analytical Chemistry, 56(1)*, 17A-27A.
23. King, J. W., Mccarthy, T. J., Grady, B. P., & Johnson, K. C. (1984). Supercritical fluid extraction. Analytical Chemistry, 56(1), 17A-27A. (n.d.).
24. Kiran, E. a. (2010). *Supercritical Fluids: Fundamentals for Application.* Springer Science & Business Media.
25. Lee, J. Y. (2003). Phase Equilibrium of Supercritical Carbon Dioxide Extraction of Lutein Esters from Marigold Petals. *The Journal of Supercritical Fluids*, 195-204.
26. Liu, S. Z. (2021). Deep Eutectic Solvents and Their Applications in Green Analytical Chemistry: A Review. . *Analytica Chimica Acta*.
27. M. de la Guardia and S. Garrigues. (2020). Challenges in Green Analytical Chemistry. In S. G. Guardia, *Challenges in Green Analytical Chemistry* (pp. 1-18). The Royal Society of Chemistry.
28. Marchetti, J. M. (2014). A review of recent process intensification in biodiesel production. *Renewable and Sustainable Energy Reviews*.
29. Namieśnik, J. &. ((2014)). *Green analytical chemistry - Theory and practice.* CRC Press.
30. Peters, C. J. (2012). Environmental Impacts of Electricity Generation: Evaluating the Importance of Carbon Dioxide Emissions. *Energy Policy*, 126-137.
31. Polaert, I. B. (2014). Production of Biodiesel from Microalgae Oil: A Critical Approach to Different Methods. *Bioresource Technology*, 455-465.
32. Ragonese, E. L. (2013). Ionic Liquid Stationary Phases for HPLC. *LC GC North America*, 204-209.
33. Ramdin, M. P. (2017). Supercritical Carbon Dioxide as a Green Solvent for Lignocellulosic Biomass Conversion. *Green Chemistry*, 3078-3103.
34. Reverchon, E. D. (2006). Supercritical Fluid Extraction and Fractionation of Natural Matter. *The Journal of Supercritical Fluids*, 146-166.
35. Richter, B. E. (1998). Application of liquid chromatography-mass spectrometry and capillary electrophoresis-mass spectrometry to the analysis of polar organic pollutants. . *Journal of Chromatography A, 794(1-2)*, 167-180.
36. S. Armenta, S. G. (2008). Green Analytical Chemistry. *TrAC Trends in Analytical Chemistry, Volume 27, Issue 6*, 497-511.
37. Sheldon, R. A. (2007). *Green solvents for chemistry: Perspectives for sustainable development.* John Wiley & Sons.
38. Sheridan, R. H. (2016). COSMO-RS Studies of Terpenes as Green Solvents. . *Journal of Chemical & Engineering Data*, 3610-3616.
39. Shimizu, K. &. (2006). Application of ionic liquids to high-performance liquid chromatography. . *Journal of Chromatography A, 1123(1)*, 1-20.
40. Smith EL, A. A. (2014). Deep eutectic solvents (DESs) and their applications. *Chem Rev*. .
41. Smith, E. L. (2014). Deep Eutectic Solvents (DESs) and Their Applications. . *Chemical reviews*, 11060-11082.
42. Subramaniam, B. a. (2013). Supercritical Carbon Dioxide Extraction of Bioactive Compounds from Algae. *Industrial & Engineering Chemistry Research*, 9509-9522.
43. Suh, S. &. (2005). Methods for life cycle inventory of a product. *Journal of Cleaner Production, 13(7)*, 687-697.
44. Tobiszewski, M. M. (2012). Green analytical chemistry - theory and practice. *Chemistry Society Reviews*, 7786-7797.
45. Tundo, P. &. (2007). *Green processes: Green synthesis.* Wiley-VCH.
46. Vinatoru, M. (2001). An Overview of the Ultrasonically Assisted Extraction of Bioactive Principles from Herbs. *Ultrasonics Sonochemistry*, 303-313.
47. Yang, S. L. (2014). Green analytical chemistry introduction. *Analytical Methods, 6(14)*, 4022-4025.
48. Zamagni, A. &. (2006). Lifecycle assessment of green analytical chemistry. *Green Chemistry, 8(7)*, 621-626.
49. Zhang Q, D. O. (2012). Deep eutectic solvents: syntheses, properties and applications. . *Chem Soc*.
50. Zhao, D. &. (2017). *Green Techniques for Organic Synthesis and Medicinal Chemistry.* John Wiley & Sons.