Use of Deep Eutectic Solvents for Plastic Waste Management : Towards a Green Solution for Recycling

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ABSTRACT

The management of plastic waste poses a significant environmental challenge, with large amounts of plastic ending up in landfills and oceans every year. Traditional recycling methods often fail, especially for complex plastics like multi-layer films and composites. Deep eutectic solvents (DES), a class of non-toxic and biodegradable solvents, offer a promising solution for plastic recycling. DES can dissolve and degrade a wide range of plastics, such as polystyrene (PS), polyethylene (PE), and polyethylene terephthalate (PET), by breaking polymer chains and transforming plastics into reusable products or valuable monomers. Compared to conventional recycling methods, DES offer several advantages, including selective dissolution of specific plastics, low environmental impact, and the potential for recycling at ambient temperatures, which reduces energy consumption. However, challenges remain, including high viscosity, selective solubility, and the need for solvent regeneration. The future of DES in plastic recycling lies in the development of improved solvent systems, their integration into industrial processes, and their use in green chemistry. Ultimately, DES offer a sustainable solution for enhancing plastic waste management and contributing to a circular economy.

Keywords : Plastic waste management, Deep eutectic solvents (DES), Recycling.

INTRODUCTION

Plastic waste management is one of the most pressing environmental challenges of the 21st century. Each year, approximately 300 million tons of plastic are produced globally, with a significant portion ending up in landfills or the oceans. While some progress has been made in plastic recycling, these efforts remain insufficient given the scale of the problem, especially for complex types of plastics. Many plastic materials, such as multi-layer plastics or thin plastic films, present considerable challenges for existing recycling systems. Traditional recycling methods, whether mechanical or chemical, face significant limitations due to the chemical composition of plastics and material contamination.

Mechanical recycling, which involves grinding and melting plastics for reuse, works effectively for certain plastics like PET (polyethylene terephthalate). However, this approach fails with more complex or mixed plastics. On the other hand, chemical recycling, which could provide a solution to these challenges, often requires the use of toxic solvents, such as chloroform, which pose environmental and health risks. Although these methods have made partial contributions to the problem, they are not enough to address the recycling of difficult-to-process plastics.

In this context, the use of deep eutectic solvents (DES), a class of environmentally friendly and non-toxic solvents, emerges as a promising alternative for plastic recycling. DES, composed of mixtures of salts and organic molecules, possess unique properties that make them particularly suitable for recycling complex plastics. These solvents can dissolve a wide range of plastics, allowing for their degradation in a controlled manner by breaking down polymer chains to transform the plastic into reusable products or monomers.One of the primary advantages of DES lies in their non-toxic and biodegradable nature, which makes them much safer for the environment compared to traditional chemical solvents. Additionally, their low viscosity and good thermal conductivity make them easier to handle on a large scale, and their ability to operate at ambient temperature reduces energy consumption during the recycling process. However, despite these significant advantages, several challenges remain, including the management of the high viscosity of certain DES, the selective solubility of plastics, and the difficulties in regenerating solvents after use.

This article explores the principles of DES and their application in plastic recycling, highlighting the advantages of this approach over conventional methods. It will also discuss the challenges that must be overcome for large-scale adoption and the future prospects for integrating these solvents into industrial recycling systems.

The Challenges of Plastic Recycling

Plastics, although widely used, are increasingly difficult to manage at the end of their life cycle. Complex plastics, such as composite plastics, thin plastic films or multilayer plastics, pose a particular challenge for existing recycling systems (1),(2). For example, multi-layer plastics, often used in food packaging, are difficult to separate and recycle, as they are made of multiple materials that cannot be processed together in conventional recycling lines (3).

Current recycling methods, whether mechanical or chemical, have limitations. Mechanical recycling, which involves grinding and melting plastics for reuse, is effective for some plastics such as PET (polyethylene terephthalate) (4),(5), but it fails with complex or mixed plastics. In addition, chemical processes often require the use of organic solvents, which can be polluting and expensive to process (6),(7).

Chemical recycling is supposed to offer a solution to these problems, but current methods often require toxic solvents, such as chloroform or other hazardous chemicals, which pose risks to health and the environment (8). It is in this context that the use of deep eutectic solvents (DES) could play a crucial role, as they offer a greener and less polluting alternative (9).

Despite their potential, several challenges remain with the use of DESs at a large scale in recycling.One of the primary challenges with using DESs in large-scale recycling is scalability. While DESs have shown promise in laboratory settings, their application at an industrial scale requires significant adaptation of existing infrastructure. The dissolution and separation processes involved in DES-based recycling are not yet fully optimized for large volumes of plastic waste. The high viscosity of many DESs can also slow down the recycling process, making them less efficient for rapid, large-scale operations. Additionally, the separation of DESs from the recycled materials after the recycling process is not straightforward. The DES must be carefully recovered and purified, which adds extra steps and costs to the recycling process.

Deep Eutectic Solvents (DES): Principles and Properties

Deep eutectic (DES) solvents are a class of solvents composed of two or more components that form a mixture with a melting point much lower than that of its individual components, **Figure 1** schematic diagram of the eutectic point on a two-component (1 and 2) phase, where EC means eutectic component (10). The dashed curve represents the melting points of a binary NADES family under different molar ratios. All unified liquid media are located in A, while applied NADES species are at or under ambient temperature as a part of A. This area should be the shape of a del operator, for which one angle point in the valley is the eutectic point. B and C represent the mixtures of EC1 and EC2 (solid/liquid or liquid/solid), and D is a mixture of EC1 and EC2 (solid/solid). The eutectic point is remarkable in that two or more compounds may combine in precise and fortuitous proportions to become mutually compatible in such as way that dramatically lowers the melting point of the mixture (10). DESs are usually formed from salts and organic molecules like amino acids, organic acids, or sugars. This eutectic mixture has unique properties , it is non-toxic, biodegradable, and can be easily recycled (11),(12).

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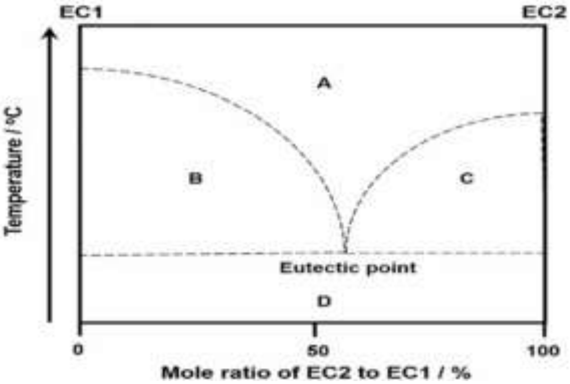
Figure 1. Schematic diagram of the eutectic point on a two-component (1 and 2) phase (10).

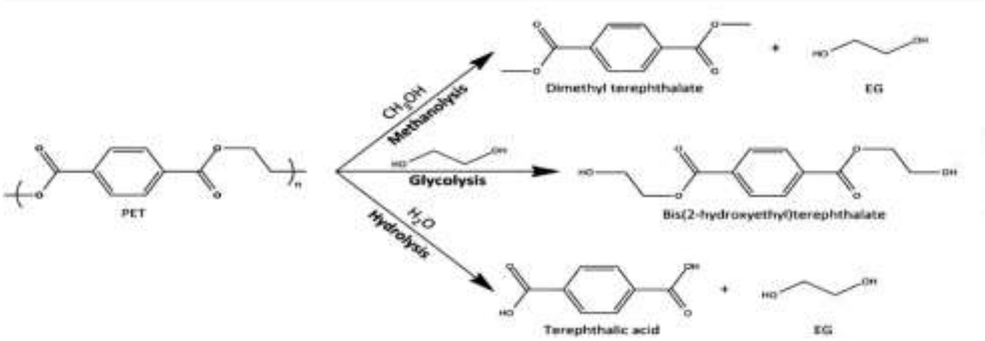


DESs have several important characteristics, such as a high solvation capacity that allows them to dissolve a wide variety of substances, including plastics, low viscosity and good thermal conductivity that facilitate their handling and use on a large scale (13), as well as selectivity that allows them to specifically dissolve certain types of plastics while preserving other materials, which is ideal for selective recycling; moreover, natural DES (14), derived from natural components like amino acids, sugars, and organic acids, are not only environmentally friendly and safe for the environment, but also have a low environmental impact and relatively low cost, making them particularly suitable for large-scale industrial applications (15).

Applications of DESs in the degradation of plastics

DES ares capables of dissolving and degrading a variety of plastics. Polymeric plastics such as polystyrene (PS), polyethylene (PE), and even PET polymer **Figure 2,** can be partially dissolved or degraded by certain types of DES. The degradation process relies on the chemical interactions between the DES molecules and the polymer chains of the plastics, which break the chemical bonds and allow the transformation of the plastic into reusable products (16).

Figure 2. General reactions involved in the chemical recycling of PET.



Here are some examples of plastics that can be treated with DESs: polystyrene, a plastic widely used in food packaging and disposable products, which can be effectively dissolved by deep eutectic solvents based on choline chloride and urea, as well as polyethylene (PE) and polypropylene (PP), often used in plastic bags and films, which can also be treated with certain DESs, although specific conditions are required for each type of plastic (17),(18).

The use of DES in the degradation of plastics is particularly advantageous in cases where mechanical recycling or other chemical methods fail. DES allow for more controlled chemical degradation, creating monomers or intermediate products that can be used to manufacture new plastics or other industrial chemicals (18),(19).

Examples of DES Applications in Real-World Industrial Contexts

In other industrial sectors, DESs have already found effective applications. For example, they are used in metaldissolution and purification **Figure 3**, where they serve as solvents for the extraction of valuable metals

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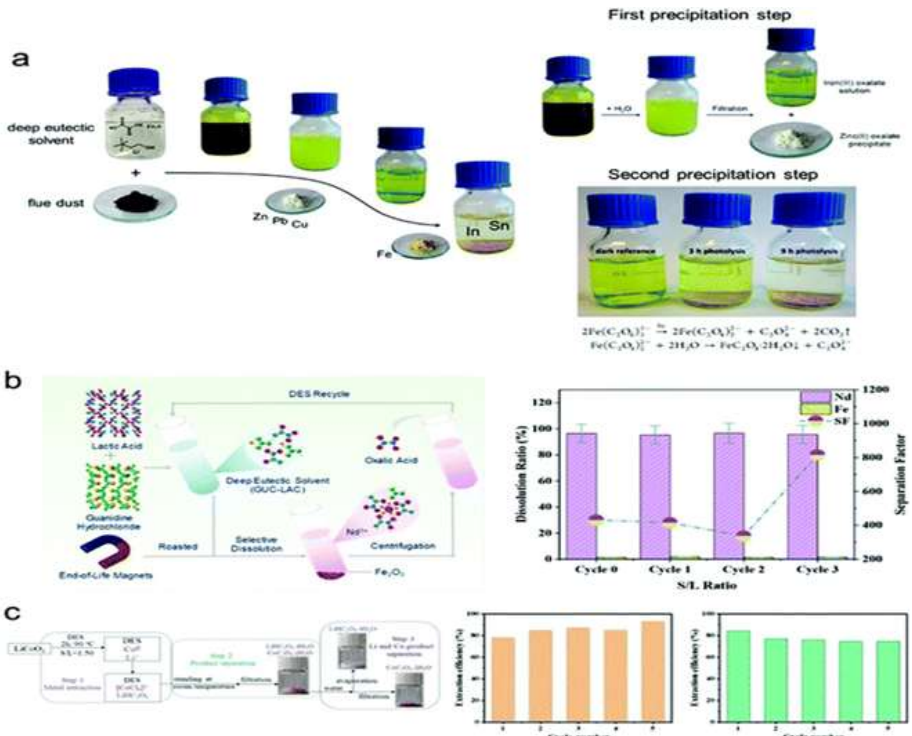
such as copper, gold, and nickel. These applications take advantage of the unique solvating properties of DESs, allowing for more selective and environmentally friendly extraction compared to traditional solvents (20). Another example is in the pharmaceutical industry, where DESs are used for the formulation of drugs and for the extraction of active ingredients from plants. Their ability to dissolve a wide range of organic compounds and their low toxicity make them promising candidates for replacing more hazardous organic solvents (21),(22),(23).

However, even in these industrial applications, the use of DESs presents challenges. The recovery and reuse of DESs is complex, and the durability of the solvents, particularly in terms of their chemical stability and reactivity over time, remains a subject of research. For instance, the adaptability of DESs to high temperature and pressure conditions in large-scale industrial processes can be limited, requiring the design of new systems or more robust solvent formulations (24).

Another challenge faced in industry is the cost-effectiveness of DESs. Although they are considered more affordable than some organic solvents, their production on a large scale is still relatively expensive, particularly if specific chemicals or renewable raw materials are used. This cost factor can limit their adoption in industries where profit margins are tight, such as plastic recycling, despite their ecological potential, the environmental impact of DESs is not entirely risk-free (25). While their toxicity is generally low, some DESs may still contain compounds that, if mishandled or contaminated by plastics or additives, could pose environmental risks. It is crucial, therefore, to expand research into their biodegradability and the waste management strategies required for their use in recycling processes, while DESs offer a promising alternative to traditional solvents for plastic recycling, their large-scale application in this domain is still hindered by challenges related to scalability, cost, solvent recovery, stability, and environmental impact. Further research and technological advancements are needed to overcome these barriers and enable the widespread adoption of DES-based recycling processes (26).

Figure 3. (a) Schematic diagram of leaching and selective extraction of zinc, iron, indium, and tin using ChCl : oxalic acid DES-based two-step precipitation procedure (left); dilution of oxaline leachate and precipitation of white zinc oxalate next to the green-colored filtrate in the first precipitation step (upper right); photograph and reaction formulations of photolysis of iron(III) oxalate solution using a UV lamp in the second precipitation step (lower right). (b) Schematic diagram of selectively leaching neodymium from end-of-life NdFeB permanent magnets by guanidine hydrochloride : lactic acid DES (left) and the recycling performance of the DES (right). (c) Schematic diagram of the one-pot extraction process using ChCl : oxalic acid DES for the recovery of lithium and cobalt from $LiCoO_2$ and the recycling performance of DES for Li extraction (middle) and Co extraction (right),(20).



Advantages of DES for plastic recycling

Deep eutectic solvents (DES) offer several distinct advantages in the field of plastic recycling, positioning them as a highly effective and sustainable alternative to conventional recycling methods. One of their primary benefits is their environmental and health safety (27). DES are composed of non-toxic, biodegradable components, such as salts and organic molecules, which are far less harmful than traditional chemical solvents that often pose risks to human health and the environment. This makes DES particularly attractive in terms of both regulatory compliance and reducing the ecological footprint of recycling processes (28),(29).

Another significant advantage of DES is their selective solubility. Unlike traditional methods that often require complex and energy-intensive separation processes, DES can selectively dissolve specific types of plastics while leaving other materials intact. This ability to target particular plastics streamlines the recycling process and minimizes contamination, improving the quality of the recovered materials (30). The selective dissolution also enables more efficient processing of mixed or multi-layered plastics, which are otherwise difficult to recycle through conventional methods (31).

In addition to their selectivity, DES offer a significant improvement in energy efficiency. Traditional plastic recycling processes often require high temperatures, which result in considerable energy consumption and associated environmental emissions. DES, on the other hand, can operate effectively at ambient temperatures, reducing the overall energy demand and contributing to a more sustainable recycling process (32). This temperature advantage not only lowers operational costs but also minimizes the carbon footprint of the recycling industry (33).

The versatility of DES in handling complex plastics is another important benefit. Multi-layered plastics, composite materials, and other difficult-to-recycle plastics can be efficiently degraded by DES, breaking down polymer chains and facilitating the recovery of valuable monomers (34). This capability is crucial in addressing the growing problem of non-recyclable plastic waste, as it opens new opportunities for recycling materials that would otherwise end up in landfills or the ocean (35).

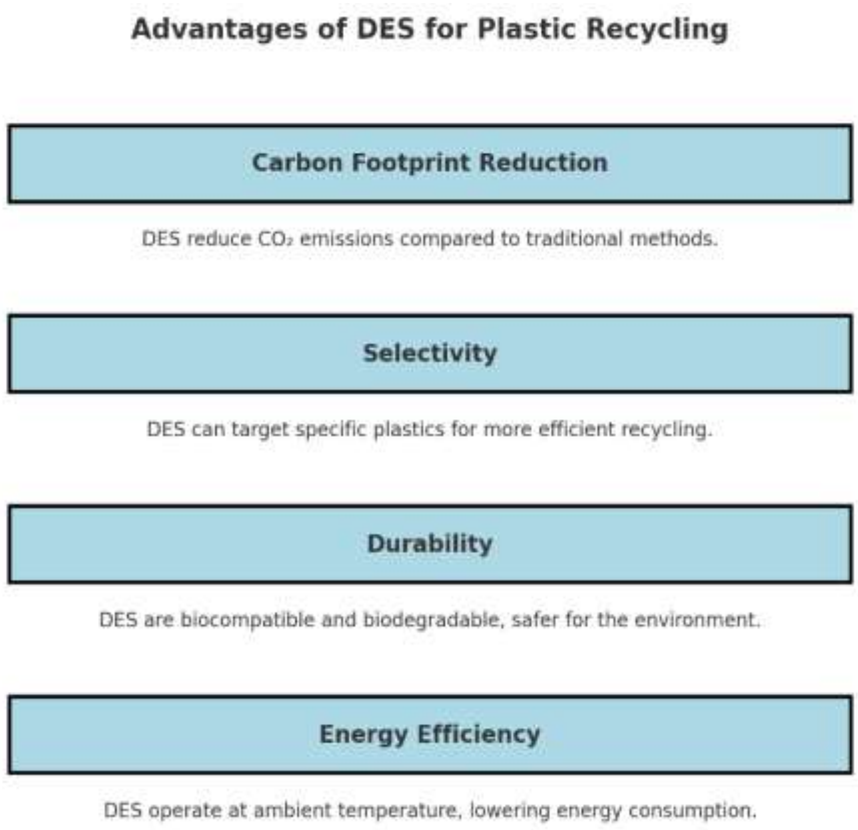
From an economic perspective, DES are also highly cost-effective. Many DES formulations are composed of inexpensive, naturally derived components such as choline chloride and urea, making them far more affordable than traditional solvents used in chemical recycling. Their low cost makes them particularly well-suited for large-scale industrial applications, where cost reduction is a major consideration (36). The low cost of DES also improves the economic viability of recycling programs, especially in regions with limited resources for waste management (37).

Furthermore, DES are recyclable and reusable, a key characteristic that enhances their sustainability. Traditional solvents often need to be disposed of after a single use, generating waste and increasing overall costs. In contrast, DES can be recovered and reused multiple times, reducing solvent consumption and minimizing waste production. This regenerative property makes DES an attractive option for large-scale and continuous recycling operations, as it further reduces both environmental impact and operational costs (38),(39).

Beyond plastic recycling, the properties of DES lend themselves to a wide range of applications in green chemistry, including catalysis, extraction, and the synthesis of eco-friendly materials (40). Their versatility in dissolving a variety of organic and inorganic substances, coupled with their low environmental impact, opens up new possibilities in sustainable chemical processes (41).

These combined advantages environmental safety, selective solubility, energy efficiency, cost-effectiveness, recyclability, and versatility make deep eutectic solvents a highly promising solution for addressing the challenges of plastic recycling (30). As research continues to optimize DES formulations and overcome existing challenges, such as viscosity and solvent recovery, their potential to revolutionize the recycling industry and support a circular economy will continue to grow (42), **Figure 4**.

Figure 4. Advantages of DES for plastic recycling



Challenges to overcome

Although DESs offer several benefits, they also come with certain challenges. One of the main issues is their high viscosity, which can complicate large-scale handling, though this can potentially be mitigated by adjusting their composition or adding complementary solvents (43). Additionally, the selective solubility of plastics in DESs is not always ideal, as some plastics require specific conditions, such as certain temperatures or concentrations. Moreover, while DESs are easier to recover than conventional organic solvents, regenerating them after use remains difficult, highlighting the need for more effective purification and recovery techniques (30),(44),(45).

Futurs prospects and innovations

The potential for deep eutectic solvents (DES) in plastic recycling is vast, with ongoing research set to open up new avenues for their application. As the need for more sustainable and efficient recycling methods intensifies, DES could play a crucial role in transforming plastic waste management.

One of the key areas of future development lies in the creation of new and improved DES formulations. Research is exploring a broader range of combinations to design DES capable of dissolving and degrading an even wider variety of plastics, especially those currently difficult to recycle, such as mixed or multi-layered plastics. Tailoring DES to meet the specific requirements of different plastics will increase the precision and effectiveness of recycling, making the process more sustainable.

Additionally, integrating DES into existing industrial recycling systems holds significant promise. Many current recycling processes rely on conventional mechanical or chemical methods that are often inefficient or require harmful solvents. By incorporating DES, recycling facilities could enhance their efficiency, reduce operational costs, and minimize environmental impacts. Moreover, the ability of DES to function at ambient temperatures could result in lower energy consumption, further improving the sustainability of large-scale recycling operations.

Beyond plastic recycling, DES have great potential in various fields of green chemistry, including biochemistry, catalysis, and chemical synthesis. Their capacity to act as solvents in diverse chemical reactions opens new opportunities for extracting valuable compounds from biomass, synthesizing eco-friendly materials, or aiding in the production of biodegradable substances. As research expands into these applications, DES could become a vital component of sustainable chemistry.

Addressing existing challenges, such as high viscosity and solvent regeneration, will be essential for the widespread use of DES. Innovations in solvent recovery techniques and the optimization of DES compositions for easier handling will facilitate large-scale adoption. Overcoming these barriers will further solidify DES as a key technology in creating a circular economy, where plastics are continually reused, minimizing waste and reducing dependence on virgin plastic production.

With ongoing advancements, DES are poised to play a transformative role in improving plastic waste management, enhancing recycling efficiency, and contributing to global efforts aimed at reducing plastic pollution.

CONCLUSION

Deep eutectic solvents (DES) offer a promising, environmentally friendly solution for managing plastic waste, representing a significant advancement in recycling technology. By providing an alternative to traditional methods, DES enable the efficient treatment of plastics that are otherwise difficult to recycle, such as multi-layered and complex plastics. Their non-toxic, biodegradable nature and ability to operate at room temperature reduce both the environmental impact and energy consumption associated with recycling processes. Additionally, DES can be tailored to selectively dissolve specific types of plastics, making the recycling process more precise and efficient compared to conventional methods.

Despite their advantages, several challenges remain, including issues related to the high viscosity of certain DES, selective solubility of plastics, and difficulties in solvent regeneration. These challenges highlight the need for further research and development to optimize DES properties, improve large-scale handling, and develop better recovery techniques for the solvents after use.

Looking ahead, the future of DES in plastic recycling appears promising. Ongoing research into new DES formulations and their integration into existing industrial recycling processes holds the potential to transform plastic recycling and contribute to a more circular and sustainable economy. Beyond recycling, DES also show considerable promise in various fields of green chemistry, such as biochemistry, catalysis, and chemical synthesis. If these challenges can be overcome, the widespread adoption of DES in plastic recycling could represent a major milestone in reducing the environmental impact of plastic waste and supporting the transition to a more sustainable, circular economy.

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