



Advancing green textile modification with deep eutectic solvents: from solvent design to industrial prospects

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ABSTRACT

This study evaluates the potential of deep eutectic solvents (DESs) as sustainable alternatives to ionic liquids (ILs) for modifying textiles. It explores the physicochemical properties of DESs, emphasizing their low toxicity, eco-friendliness, and versatility in processing textile materials for diverse applications. This review initiates DESs for modifying natural and synthetic fibers/fabrics, highlighting their potential to revolutionize sustainable textile manufacturing. Moreover, it emphasizes the recent advancements in DES research for textile applications, identifying the important scientific issues and pointing out interesting research directions that could further enhance our understanding of these solvents and their applications. Although DES properties and general applications have been extensively reviewed, no previous work has specifically addressed their potential for textile modification. This review is anticipated to inspire intensified research efforts and hasten industrial adoption of DESs as sustainable solvents for textile applications.

1. Introduction

Deep eutectic solvents were first introduced as a green solvent class in 2004 via the synthesis of choline chloride-urea mixtures in specific molar ratios [1], representing a major advance in sustainable chemistry [2]. These solvents are variously termed in scientific literature as Low Transition Temperature Mixtures (LTTMs), Deep Eutectic Ionic Liquids, or Low-Melting Mixtures, reflecting different aspects of their physicochemical behavior. DESs consist of two fundamental components: hydrogen bond acceptors (HBAs) and hydrogen bond donors (HBDs). These solvents can be prepared through multiple synthesis routes, including conventional methods (freeze-drying, grinding, thermal evaporation) and modern assisted techniques (microwave or ultrasound irradiation), typically accompanied by mixing procedures. DESs are prepared by mixing precisely measured HBA and HBD components under controlled heating (<100 °C) to facilitate eutectic formation. The resulting mixture is subsequently cooled to room temperature (25±2 °C) under static conditions to yield the final product [3,4]. DESs, with their low melting points, affordability, and availability, serve as versatile and cost-effective solvents or electrolytes. These properties contribute to

their widespread use and interest in academic and industrial research [1,5–7]. DESs exhibit many similar properties to ILs, like high thermal stabilities [8,9], low volatility [10,11], low vapor pressures [12], and tunable polarity [13]; they are frequently identified as a class of ILs. This positions DESs as an excellent substitute for approximately 600 volatile organic compounds currently utilized in extensive scientific research and industrial applications [14]. Ionic liquids are frequently constrained by three major drawbacks: high cost, environmental incompatibility, and toxicity. Deep eutectic solvents overcome these limitations through their economical synthesis [15], non-toxic nature [16–18], biodegradable characteristics [16,19], and simple preparation processes.

The boom in advanced technologies has expanded the functionality of clothing, maintaining aesthetic appeal while offering excellent protection against environmental exposures. For instance, polysaccharide-based modifications of textile materials have been applied as essential building blocks for fibers, coatings, and stabilizing components [20–23]. However, textile industries are considered one of the major contributing factors in creating pollution, and it has been estimated that 20 % of all water pollution is caused by textile treatments like dyeing and processing [24,25]. Traditional textile dyeing practices create

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disproportionate environmental damage, with each ton of dyed fabric potentially contaminating 200 tons of freshwater through toxic effluent discharge. Thus, it has been reported that the wastewater produced by the textile industries is extensively colored and generally contains complex mixtures of chemicals, including dyes, heavy metals, and detergents [26–28]. As wastewater treatment techniques are costly and energy-intensive, eco-friendly chemicals and techniques must be employed during textile processing and manufacturing.

In the past few years, several studies have been conducted to evaluate the DESs' properties and their utilization in different fields, as shown in Fig. 1. Different study results revealed that DESs can be used in numerous applications, particularly in chemical processing and biotechnological applications like green solvents [29], catalytic systems [30], reaction media [31], functional substrates [15], extraction and purification agents [32], gas capture or absorption [33], nanotechnology for nanomaterials preparation [34], and many biological applications [35]. Scientists show a keen interest in DES utilization in numerous fields because of their superior green and controllable physicochemical features. Researchers are increasingly prioritizing eco-friendly materials to minimize environmental challenges [36,37].

While deep eutectic solvents show exceptional promise for sustainable textile manufacturing, their industrial adoption faces significant barriers, including unclear scale-up parameters and missing economic feasibility data [38,39]. This review directly addresses these challenges through its deliberate structure: the comprehensive DES fundamentals coverage in the first part of this review, establishes critical property-performance relationships (molar ratios governing cellulose dissolution yields), viscosity affecting dye penetration that determine real-world viability, while the textile applications translate these fundamentals into actionable solutions for waste reduction [40] and equipment adaptation. By first providing the essential toolkit for DES selection and optimization, then demonstrating textile-specific implementations, we bridge the gap between laboratory potential and industrial requirements, precisely the knowledge needed to advance DES beyond niche applications toward mainstream textile sustainability. To date, no comprehensive review has reported the role of DESs in the sustainable processing of textile materials for diverse applications. Although our team has previously published a book exploring the broader application of DESs in the textile industry [41], a focused and in-depth review on this emerging area remains absent from the literature. This work systematically reviews DES systems for textiles, showcasing their transformative potential in sustainable functional fabric production.

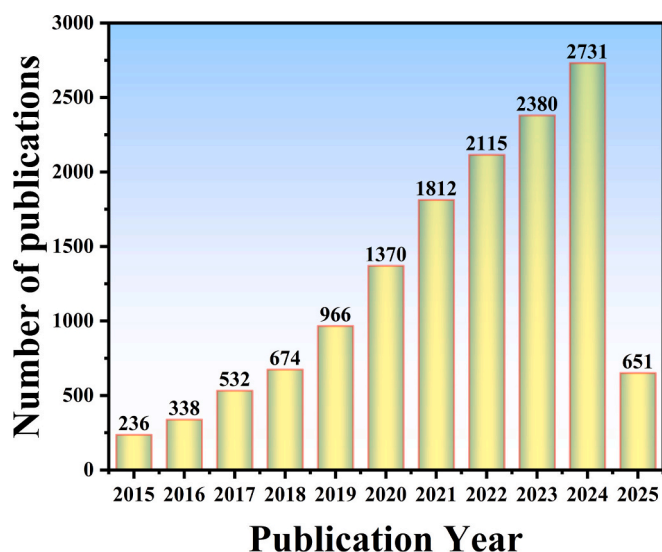


Fig. 1. Reported studies for eutectic solvents from 2015 to 2025 (Web of Science search (April 10, 2025); keyword: 'Deep eutectic solvent').

2. Basics of deep eutectic solvents

2.1. Properties

The growing interest among researchers in DESs can be attributed to their excellent characteristics. DESs exhibit various tremendous properties such as low evaporation tendency, flame resistance, low vapor pressure, and high resistance to chemical and thermal degradation. Moreover, DESs offer tunable physicochemical characteristics for various specialized applications, because of their wide range of possible components [42]. The comprehensive discussion of some of the properties, including fluid density, viscosity, ionic conductivity, surface tension, and molecular polarity, will provide valuable insights into the potential applications and behavior of DESs.

Density can be called a fundamental physical property of liquids, which exhibits a superior role in defining the properties of DESs. Most of the reports revealed the higher density values of DESs as compared to water. Generally, the DESs' density values remain between 1.0 to 1.3 g/cm³ at room temperature. Specifically, the presence of metal salts in DES composition tends to have higher densities, falling within the range of 1.3 to 1.6 g/cm³ [43]. Moreover, certain hydrophobic deep eutectic solvents deviate from the general trend, exhibiting lower densities compared to water [44]. By revealing details about molecular packing and intermolecular dynamics, these density values play a crucial role in evaluating the physical properties of DESs and assessing their practical applications [45].

Viscosity has been considered another important factor in the characterization of DESs, particularly in separation applications such as adsorption, membrane-based filtration, or solvent extraction. Generally, viscosity is defined as the measure of a fluid's resistance to deformation under shear stress. The viscosity of deep eutectic solvents has been extensively investigated in numerous studies [46]. It signifies that fluids with low viscosities flow more easily, while those with higher viscosities exhibit slower flow rates. An accurate understanding of DES viscosity is fundamental for enhancing their performance in diverse applications, allowing researchers to make strategic choices in separation processes. In general, deep eutectic solvents are identified as highly viscous liquids at room temperature, with viscosities (η) typically exceeding 100 mPas [47]. This high viscosity can pose challenges when it comes to their practical utilization in commercial applications, including catalysis, synthesis, and other industrial processes. DESs exhibit higher viscosity compared to many other compounds, which can hinder mass transfer and constrain their performance in particular uses [48]. The viscosity values of DES mixtures can be adjusted by various factors such as changing the composition of their components [49,50], the molar ratio of the components [51], temperature variations [1,52–55], and the presence of water [56–58]. Additionally, the surface tension (ST) of deep eutectic solvents is another factor that defines the quality and significantly influences their ability to interact with other compounds. Among interfacial characterization techniques, ST analysis offers a fundamental approach to probing cohesive interactions in a liquid surface [59]. It gives liquids the ability to bear small weights (water striders, for example) and maintain cohesive forces between molecules. For example, mosquito eggs can float easily on the water's surface due to surface tension, causing ideal conditions for offspring breeding. Additionally, toothpaste's reduced ST improves its functional efficiency, enabling better coverage and cleaning action in the mouth. ST has an effective role in wetting, bubbling, permeability, and lubrication [60]. In contrast to the high surface tension of water (72.8 mN m⁻¹), the majority of deep eutectic solvents exhibit markedly lower values, typically ranging from 30 to 60 mN m⁻¹. Deep eutectic solvents, examined in various studies, have been reported to exhibit the lowest surface tension values (23.69 mN m⁻¹, 27.07 mN m⁻¹, and 28.35 mN m⁻¹) using different molar ratios of DES components [61]. However, higher surface tension values have also been observed in the case of ChCl:d-Fructose as 70.40 mN m⁻¹, 75.60 mN m⁻¹, 74.00 mN m⁻¹, and 75.00

mN m^{-1} when the molar ratios were taken as 1:1, 1.5:1, 2:1, and 2.5:1, respectively [62]. Similarly, higher surface tension values have been observed (71.57 mN m^{-1}) in deep eutectic solvents prepared by ChCl: Glucose components when the respective molar ratio was 2:1 [63]. The surface tension (γ) of deep eutectic solvents varies systematically with the molar composition of their hydrogen bond donor/acceptor components. Specifically, a higher ST is generally associated with an increased proportion of the hydrogen bond acceptor in the DES formulation [51]. In a recent study, ST variation in different DES systems has been observed [64]. This study systematically investigated the surface tension of different DESs, revealing that both HBD and HBA types significantly influence surface tension, with higher HBA ratios generally leading to increased ST values. Additionally, the study results demonstrated that water sharply increases surface tension when its mole fraction exceeds 0.9, whereas the incorporation of other solvents generally leads to a progressive reduction in surface tension with increasing concentration. A temperature rise from 20 to 60 °C results in a noticeable reduction in surface tension values. These insights offer valuable guidance for the tailored design of DESs in interfacial and colloidal applications.

2.2. Greenness of deep eutectic solvents

Deep eutectic solvents are emerging as promising green alternatives to conventional organic solvents in various applications, including textile processing. In textile dyeing applications, bio-based DES systems demonstrate exceptional potential to simultaneously reduce wastewater generation by up to 60 % and improve color fastness properties [40]. Natural deep eutectic solvents (NADES), made from primary metabolites like amino acids and sugars, represent a particularly promising subset of DES [65]. However, comprehensive assessments of DES greenness are crucial, as claims about their environmental friendliness may sometimes be overstated [66]. So there must be a wide discussion on the greenness of deep eutectic solvents prior to being used for textile applications.

Ionic liquids, generally called green solvents, have been extensively used in different applications primarily because of their lower vapor pressure properties. However, recent studies have challenged this perception and highlighted the toxicity and biotoxicity associated with ILs, suggesting that they may not be inherently environmentally friendly [67]. DESs demonstrate significant potential to replace ILs, providing comparable solvent performance while overcoming limitations through easier preparation, lower cost, and improved sustainability metrics. While DESs often exhibit greener properties than conventional solvents, their sustainability must be assessed based on toxicity, biodegradability, and sourcing of individual components [68]. Despite this, the green characteristics of DESs depend on their specific formulation and composition. In various types of deep eutectic solvents (as detailed in Table 1), the type I, II, and IV DESs typically contain metal salt constituents with distinctive toxic properties [69]. Consequently, type III eutectics generally contain a low inherent toxic element, including a variety of amides and polyols such as urea, glycerol, fructose, ethylene glycol (EG), and erythritol [70]. Some DES formulations have been done by incorporating food-grade ingredients, further enhancing their potential applications. Matthijs et al. [71] demonstrated the environmental impacts of deep eutectic solvents containing choline chloride and

ethylene glycol in a specific area of electroplating application. The study indicated that the individual components comprising DESs demonstrate both environmental compatibility and high biodegradability. Results showed the electroplating process primarily impacted the environment through (1) heavy metal emissions, (2) rinsing solution discharge, and (3) electrolytic byproducts from imperfect electrode reactions. The high viscosity and surface activity of the DES electrolyte led to adherent residual films on substrates and plating apparatus after processing. Due to its higher viscosity compared to aqueous solutions, the DES electrolyte showed enhanced drag-out effects, with substantial solution retention in micro-cavities and subsequent transfer to rinse baths, exacerbating both bath depletion and effluent contamination. The authors acknowledged that the drag-out phenomena had the most significant influence on the environmental consequences of the process, with a three times higher impact compared to conventional solutions because of the higher viscosity of deep eutectic solvents. However, the researchers specifically emphasized that the choline chloride/ethylene glycol DES system exhibited environmental compatibility compared to most ionic liquids. Additionally, Matthijs et al. [71] suggested that the rinse water could be treated with ion exchange methods to eliminate any metals present in it. While both HBD and HBA of a DES system can be considered environmentally safe because of their low individual toxicity, however, the mixture of these components cannot be assumed to be nontoxic and inherently "green. Deep eutectic solvents possess unique properties that are distinct from their components. In a comprehensive study, Hayyan et al. [72,73] assessed both the toxicological and cytotoxic effects of DES systems comprising choline chloride paired with multiple H-bond donors (glycerol, EG, triethylene glycol, and urea). Their findings emphasized that the choline chloride-based DES systems demonstrated consistently higher cytotoxicity than any of their pure constituent. The toxicity and cytotoxicity profiles varied significantly with the molecular structure of DES components, particularly their functional groups and chain length. Thus, these findings necessitate a comprehensive evaluation to define the toxicity of DESs before confidently claiming their nontoxic and biodegradable nature.

2.3. Deep eutectic solvent preparation techniques

DES preparation involves combining different components in specific molar ratios that significantly influence their properties and effectiveness [75,76]. Temperature also plays a crucial role, with the highest dielectric constant observed at 25 °C for various DESs. DES preparation methods vary, each with advantages and disadvantages, and their polarity can be classified using different scales [77]. These factors are essential for optimizing DES performance in textile applications, such as fiber treatment and extraction processes. So this section will discuss the DES preparation techniques and factors affecting the DES properties.

Generally, a common method is used in the preparation of DES only by heating at a specific temperature and stirring DES ingredients together under inert atmospheric conditions until a uniform liquid is finally formed. Unlike traditionally prepared solvent mixtures, DES doesn't need any additional solvent in the preparation process. Thus, unlike ionic liquids and conventional organic solvents, DESs have tremendous practical advantages as no purification steps are required in their preparation. Vacuum evaporation, mechanical grinding, and lyophilization represent three established alternative methodologies for DES synthesis. In the evaporation-based synthesis method, DES components are initially mixed with deionized water, with subsequent removal of the aqueous phase through controlled evaporation at 50.15 °C under reduced pressure. The prepared solution was then stored in a desiccator until no further weight change was observed. The grinding method requires mixing DES components in a mortar and milling under N_2 atmosphere until a clear and uniform liquid forms. However, the freeze-drying technique for DES preparation consists of first dissolving the HBA and HBD in water at an approximate 5 wt %

Table 1
Classification, composition, and examples of DES [69,74]

Deep eutectic solvent type	Formation	Example
I	Organic salt + metal chloride	Choline chloride–ZnCl ₂
II	Organic salt + metal chloride hydrate	Choline chloride–CoCl ₂ ·6H ₂ O
III	Organic salt + HBD	Choline chloride–urea
IV	HBD + metal chloride hydrate	Urea–ZnCl ₂

concentration. Later on, to create a homogeneous liquid, two mixtures are uniformly blended, rapidly frozen, and then subjected to freeze-drying [78]. Fig. 2 exhibits the major components used as HBD and HBA in DES synthesis.

The heating and stirring method is a widely used and straightforward technique for synthesizing deep eutectic solvents involving mixing HBAs and HBDs in specific molar ratios under controlled temperature and agitation. The mixture is then passed through a gentle heating process, typically within the range of 50–100 °C, while being continuously stirred. Dai et al. [80] reported a technique to explain this phenomenon, the variations were addressed by adding minimal water to the compounds, then heating them at specific temperatures (less than 50 °C) in a water bath with constant stirring, which produced a homogeneous, clear solution in a certain time (30 to 90min). This alteration of temperature and stirring procedure is typically used when DESs are produced by natural substances. In another report, when DESs were produced at temperatures over 100 °C by using main constituents ChCl and R-COOH, impurities like ester and HCl were generated, possibly from reactions between the COOH group and ChCl's chloride[57].

Subsequently, researchers introduced an alternative mechanochemical synthesis method called grinding, where DES components are ground at ambient temperature using a mortar and pestle. This approach facilitates molecular interactions through continuous mixing and

grinding while avoiding the formation of undesirable by-products associated with high-temperature synthesis [81]. Although the resultant DES shows purer properties as compared to a general heating method, the heating approach is more appealing because it's easy to use. Another widely adopted method is the evaporation technique, which incorporates three components during synthesis [82]. The system incorporates a third component, typically water, which serves as a solvent medium to facilitate the dissolution of both the HBD and HBA. A rotating oven was used to help the mixture evaporate at a specific temperature after the dissolving process. The resultant liquid is dehydrated to obtain a consistent weight while being stored in a silica gel desiccator [83]. The least-applying method, the "freeze-drying approach," was studied in 2009 by Gutierrez et al. [78] and is based on freeze-drying of several DES equivalents' aqueous solutions. However, this method is rarely used since it is impossible to eliminate all the water from the DES system, as water molecules react with DES components and are trapped in the structure of synthesized DES [84]. Table 2 shows the formation of DES by using various types of HBAs and HBDs.

2.3.1. Impact of time and temperature on DES preparation

Unlike conventional solvents, DES preparation requires particular attention to temperature and time optimization due to its complex formation mechanism. When water is absent from the combination, the

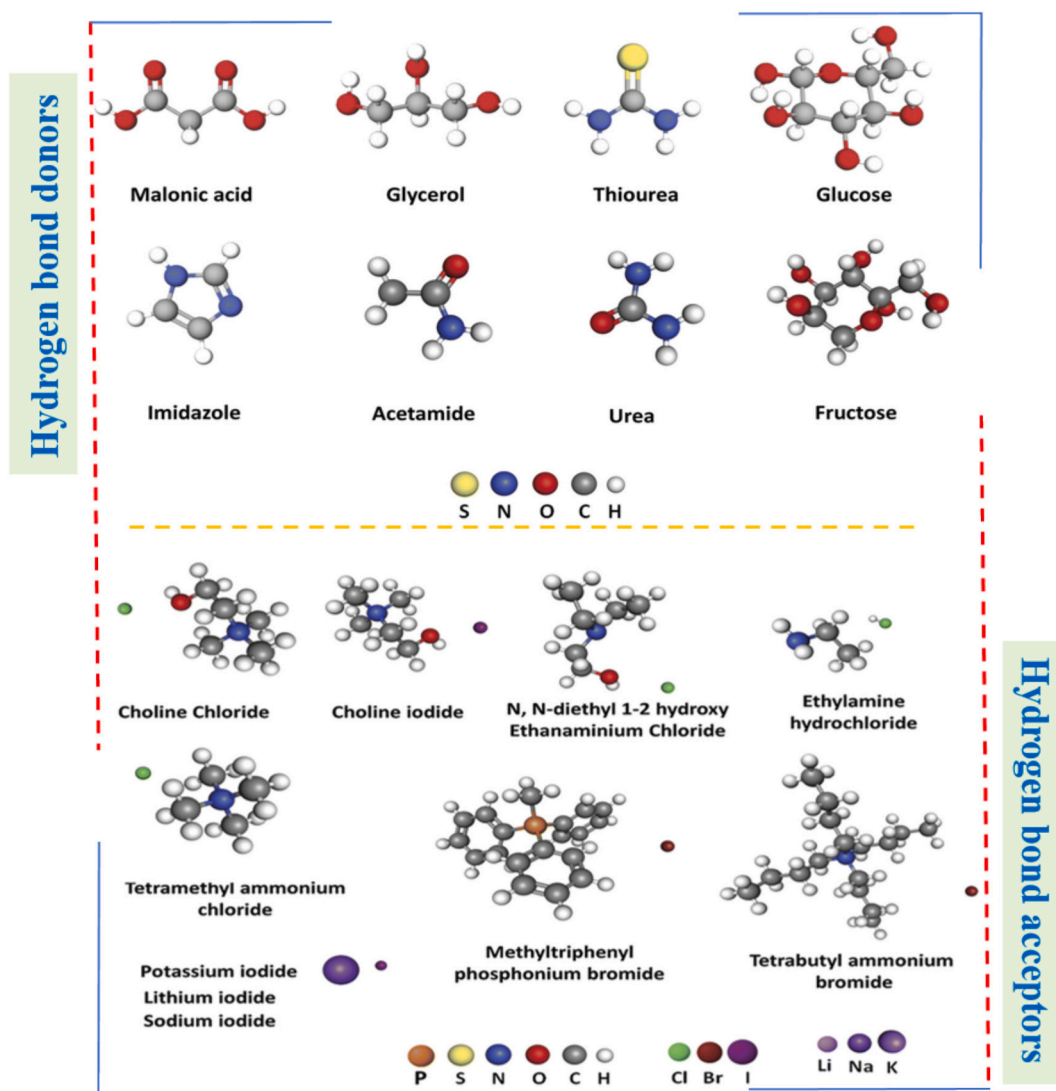


Fig. 2. Different kinds of HBAs and HBDs used in DES preparation systems, reproduced from [79]

Table 2

DESs formation obtained by the interaction between HBA and HBD molecules

Sr. No	HBA	HBD	Molar ratio	References
1	Choline chloride	urea	1:2	[53]
2		Thiourea	1:2	
3		1-Methylurea	1:2	
4		1,3-Dimethylurea	1:2	
5		Acetamide	1:2	
6		Benzamide	1:2	[1]
7		Oxalic acid	1:1	
8		Malonic acid	1:1	
9		Adipic acid	1:1	[1,85]
10		Succinic acid	1:1	
11		Phenyl acetic acid	1:2	
12		Phenylpropionic acid	1:2	
13		Tricarballic acid	2:1	
14		Citric acid	1:2	[85]
15		Trifluoroacetamide	1:2	
16		Ethylene glycol	1:2	
17		Glycerol	1:2	[49]
18		1,4- Butanediol	1:2	
19	Ethylammonium chloride	Urea	1:1.5	[54]
20		Acetamide	1:1.5	
21		Trifluoroacetamide	1:1.5	
22	Methyltriphenylphosphonium bromide	Glycerine	1:1.75	[86]
23		Ethylene Glycol	1:4	
24		2,2,2-Trifluoroacetamide	1:8	
25	Benzyltriphenylphosphonium chloride	Glycerine	1:5	
26		Ethylene glycol	1:3	
27		2,2,2-Trifluoroacetamide	3:1	[45]
28	N, N-Diethyl ethanol ammonium chloride	Glycerol	1:2	
29		Ethylene glycol	1:3	
30		2,2,2-Trifluoroacetamide	1:2	
31	Methyl triphenyl phosphonium bromide	Glycerol	1:2	
32		Ethylene glycol	1:4	
33		2,2,2-Trifluoroacetamide	1:8	[87]
34	Zinc chloride	Urea	1:3.5	
35		Acetamide	1:4	
36		Ethylene glycol	1:4	[88]
37	Zinc perchlorate	Hexanediol	1:3	
38		Acetamide	1:4	
39	Magnesium perchlorate	Acetamide	1:5	[89]
40		Citric acid	1:2, 1:3	
41		Malic acid	1:1, 1:2, 1:3	[90]
42	Choline chloride	Malic acid	1:1, 1:2, 1:3	
43		Aconitic acid	1:1	
44		Glucose: water	1:2	[90]
45		Fructose: water	1:2	
46		Sucrose : water	1:2	

typical temperature range for the "heating and stirring preparation technique" usually falls between 80 and 100 °C [91–93]. However, the temperature is typically lower than 50 °C [93–95] when employing water in the synthesis process, especially when using the natural components in DES preparation; 80 °C has also been reported for DES preparation in various studies [96–99]. In certain situations, DES formation at room temperature is achievable in two specific cases: (i) systems containing phenolic hydrogen bond donors with chloride-based acceptors or (ii) when all constituent chemicals are liquids at the processing temperature. However, specific methods are involved, such as stirring or vortex agitation, to complete the synthesis process [100,101]. When no water is employed and the production process is conducted at a temperature above 80 °C, the typical synthesis time is evaluated between 1 and 5 hours [102–104]. In contrast, on addition of a specific amount of water, the time reduces below 90 minutes, as acknowledged in [80,105,106]. Similarly, time reduction has been noticed when imidazolium salts were used in the DES preparation process [107–109]. In addition, reaction time was dropped when the production process was accomplished by agitation or a vortex [100,101,110], even leading to a synthesis time of less than 5 minutes. DES properties emerge from synergistic effects between (1) specific HBA-HBD interactions and (2) component molecular volume. This is demonstrated by ammonium persulfate-containing systems, where the large anion radius and

molecular weight yield denser solutions [62]. Recent investigations [111] demonstrated an inverse correlation between temperature and density for both glycerol and DES systems (Fig. 3a). This phenomenon was ascribed to enhanced molecular mobility and conformational flexibility at elevated temperatures, leading to increased molar volume and consequent density reduction [111,112]. Similarly, the electrical conductivity of deep eutectic solvents shows a positive response with temperature increase, as shown in Fig. 3b. Results showed that this increase in conductivity was because of a decrease in viscosity, leading to an improvement in the mobility of ionic species [113]. The trend of decreasing viscosity with the increase in temperature (Fig. 3c) has also been examined in the study. Thus, the experimental results demonstrated that elevated temperature enhances molecular thermal motion in DES systems, consequently weakening intermolecular forces and significantly reducing viscosity [112].

Additionally, surface tension (ST) exhibits a strong correlation with temperature deviation. As shown in Fig. 3d, ST decreases with increasing temperature during DES preparation. This trend may occur because the dissolved salt disrupts the hydrogen bonds between glycerol molecules [51]. Fig. 3d presents the temperature-dependent surface tension measurements of synthesized deep eutectic solvents.

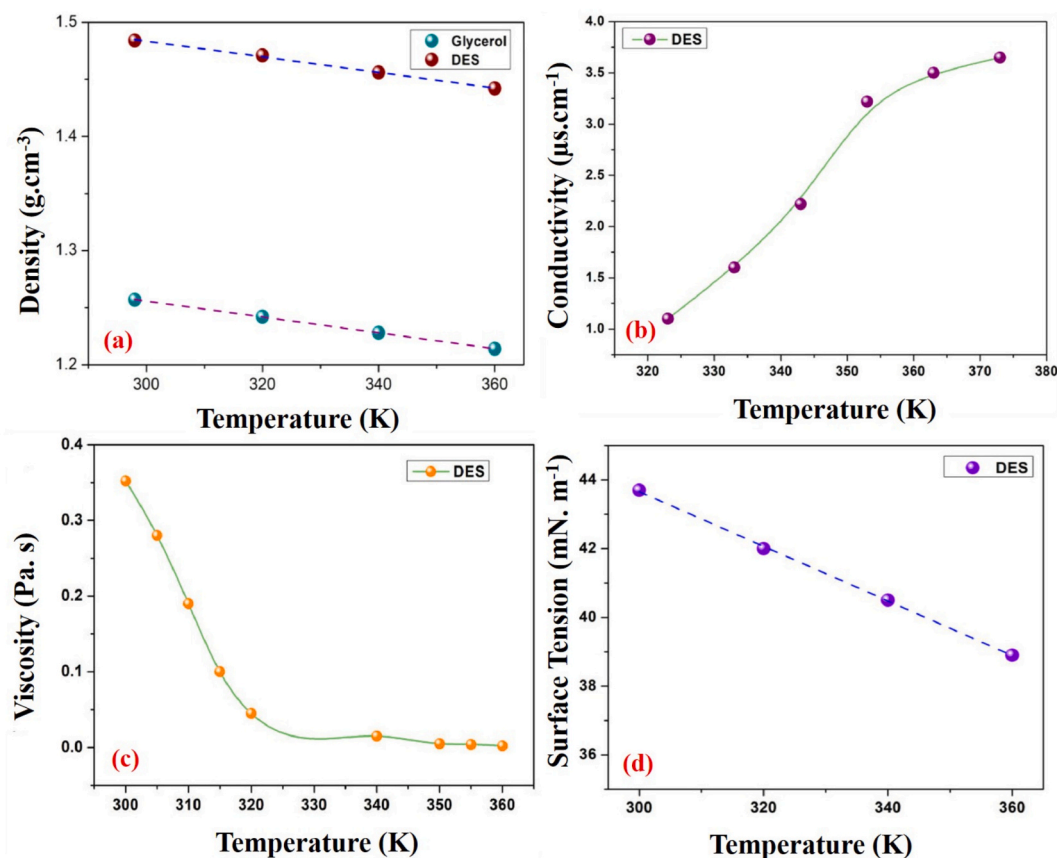


Fig. 3. Temperature impact on glycerol/DES densities (a), electrical conductivity (b), viscosity (c), and DES surface tension (d), adopted from [112].

2.3.2. Impact of molar ratio in DES preparation

The ratio at which the components are mixed, known as the molar ratio, is fundamental in determining both the production and eutectic properties of DESs. An incorrect molar ratio between the components can prevent the proper formation of DES. As a result, parameter optimization in DES synthesis has been considered a crucial process [114]. Some molar ratios of various DES examined in different mixtures conducted to date are employed more frequently than others, highlighting the fact that this mostly depends on the component that functions as an HBA. In different studies, the molar ratio 1:2 (HBA/HBD) for DES systems composed of ChCl as HBA has been noted, while other ratios, including 1:1, 1:3, and 1:4, have also been commonly used [102,115–120]. Quaternary ammonium salts exhibit optimal performance at 1:1 and 1:2 molar ratios, as extensively documented in studies employing ratios of 1:1–1:5 [103,121–123]. In contrast, systems incorporating quaternary phosphonium or imidazolium salts display significantly greater variability in physicochemical properties, with reported evaluations spanning non-stoichiometric ratios (e.g., 1:1, 1:2, 1:3, 2:5, 3:7) [107–109]. For sugar-containing DESs, regardless of the hydrogen bond acceptor (HBA) identity, synthesis typically requires controlled water addition to mitigate viscosity challenges, as demonstrated in prior work [94,124,125].

3. DES Design Strategies for Textile Processes

The consumption of textiles in the European Union involved about 400 m² of land, 9 m³ of water, and 391 kg of raw materials, which shows an excessive amount of carbon emission (270 kg CO₂). In this regard, textile was reported as the 3rd largest source of water degradation and land degradation in 2020 [126]. While the average European citizen purchases 26 kg of new garments and discards approximately 11 kg annually. Of this, only 1 % is recycled back into new textiles [127].

Textile wet processing, essential for achieving structural properties, generally includes desizing, scouring, bleaching, mercerization, dyeing, and finishing, traditionally employing water as the solvent [128]. Protection against weather extremes and bacteria is a key textile function, whereas wearing comfort is significantly affected by the coloration technique. Dyeing involving complex physicochemical processes depends essentially on the interplay between fabric and dye, selected dyeing technique, and the type of dyes applied.

As DES has been used as a solvent for textile dyeing, before selecting DES components for textile dyeing, the most important functionalities of the solvent should be considered, which are as follows [128,129]:

- Fiber's wetting and swelling facilitate the dye diffusion and internal fixation into the fibers.
- Facilitating dye/auxiliary dissolution/dispersion to ensure uniform distribution (leveling) during wet processing, while allowing efficient washing to remove unfixed components and impurities afterward.
- Solvent-induced fiber plasticization: Breaks/weakens intermolecular polymer bonds, lowering the glass transition temperature (T_g). This reduces rigidity and modulus, alters hydrophobicity, and enables lower dyeing temperatures.
- Facilitates heat and mass transfer essential for uniform wet processing.

DESs have been reported as ecological substitutes to traditional solvents, providing excellent physicochemical properties and a wide range of applications [130]. However, the balanced design of deep eutectic solvents exhibited the superior HBD and HBA selection in a supreme consideration [131]. Natural deep eutectic solvents, generally obtained from specific materials (sugar and amino acids), exhibit an eco-friendly choice for numerous chemical processes [132]. The presence of

hydrogen bonding between DES components causes to reduction in the freezing point, which is essential for solubilization capacity. Additionally, DES systems are excellently conductive, showing that ionic species that are separated can diffuse through the medium [133]. Recent academic and industrial advancements have enabled the design of hydrophobic deep eutectic solvents, offering sustainable solutions to water-sensitive processes and replacing toxic volatile organic compounds (VOCs). Thus, to excellently harness the DES potential in various field especially in textile, it's crucial to understand their physicochemical properties such as polarity, viscosity, and conductivity. Strategic DES deployment in textiles hinges on property-process correlations (polarity → fiber compatibility, viscosity → penetration kinetics), forming design rules that align solvent composition with application targets [132]. However, optimizing these attributes for specific end uses requires deliberate selection and formulation of DESs with targeted physicochemical properties. Thus, in this regard, a critical first step in DES designing for silk processing is matching solvent–substrate interactions to obtain the required results. For example, for muga silk treatment, the DES system involving chitosan and glycerol was introduced by Grala et al. [134], which exhibited the excellent ability of chitosan to form hydrogen bonds with fibroin and glycerol's role as a plasticizer. A chitosan-glycerol-based DES system was introduced to muga silk for 30 min and results of the study revealed that because of molecular cross-linking, the thermal stability of obtained samples was increased by ~28 °C. Meanwhile, moisture regain was increased by ~3.7-fold because of glycerol plasticization. Moreover, structural transition was observed from ordered β -sheets toward more amorphous conformations which shows that DES composition directly guided structural rearrangement. Table 3 shows the summary of DES systems that have been used in various studies for textile dyeing.

Cellulose-based textiles are extensively used in various applications because of their excellent, sustainable, and versatile properties. Cellulose is the most abundant biopolymer on earth, exhibiting superior structural characteristics for textile materials production [141,142]. Cellulose fibers have been used in diverse applications, such as in apparel, home textiles, and in non-woven medical textile materials (gauze, etc). The production of cellulose-based textiles with modified properties, such as antimicrobial and biostable characteristics, provides excellent advantages because of the easy access to the cellulosic material and simple production technique [143]. Recently, textile industries have been seeking various sustainable approaches for textile production. In response, cellulose-based materials are continuing to offer a significant role in addressing the environmental and functional demands. Reports revealed that cellulose structure greatly influences its affinity for dissolution. Cellulose primary structure involves a linear unbranched polymer of β -glucopyranoside residues, which are associated with 1 → 4 β -glycosidic bonds. The presence of two hydrogen bonds stabilizes the glycosidic bond and makes the structure of cellulose more rigid. These two bonds are present between C6 and the C2 hydroxyl and between the C5 oxygen and C3 hydroxyl [144]. However, the secondary structure of cellulose is a combination of alternative crystalline and amorphous regions. Generally, cellulose has strong resistance against microbial degradation because of its supramolecular hydrogen bonding structure, and due to this rigid structural behavior, cellulose is insoluble in most solvents [145]. The affinity of cellulose dissolution is connected with the breaking of hydrogen bonding in crystalline regions, where derivatizing solvents respond chemically with hydroxyl groups and successively break the hydrogen bond network. Alternatively, the non-derivatizing solvents destroy the inter- and intra-molecular hydrogen bondings. The breaking or destroying of hydrogen bonds by non-derivatizing solvents generally occurs in two ways: either by formation of hydrogen bonds between solvent components and hydroxyl groups of cellulose or by bonding between hydroxyls of cellulose molecules and metal ions present in the solvent medium [146,147]. For the results, generally, cellulose dissolution is measured by a polarizing microscope. As compared to conventional ionic liquids (composed of one type of

Table 3

Selected DES systems that have been investigated in textile dyeing

Textile material	Deep eutectic solvents	Abbreviations and molar ratio	Findings	Ref.
Polyester	Choline chloride-Ethylene glycol	ChCl-EG = 1:2	Successful dissolution/stability of CI Disperse Blue 79 & Red 343 in ChCl/EG DES NADES (ChCl-EG) effectively replaced toxic metal mordants in natural dyeing, NADES reuse >10 cycles without performance loss	[135]
Cotton	Choline chloride-Ethylene glycol	ChCl-EG = 1:2	DES enabled salt-free dyeing of cellulose nanofibers (CNF) with anionic reactive dyes	[136]
CNF	Choline chloride-Ethylene glycol	ChCl-EG = 1:2	Thymol-menthol HDES enabled salt-free reactive dyeing of cotton, ChCl-oxalic acid DES enabled dual physical etching + chemical modification of PLA filament surface.	[37]
Cotton	Thymol-Menthol	Thy-Men = 1:1	DES enabled adsorption/dyeing of anthraquinone dyes onto polyester fabrics (PETFs) under mild ("facile") conditions	[137]
Polylactic Acid	Choline chloride-Oxalic acid	ChCl-OA = 1:1	DES enabled adsorption/dyeing of anthraquinone dyes onto polyester fabrics (PETFs) under mild ("facile") conditions	[138]
Polyester	Choline chloride-Malonic acid	ChCl:MalAc = 1:1 to 1:4	DES enabled adsorption/dyeing of anthraquinone dyes onto polyester fabrics (PETFs) under mild ("facile") conditions	[139]
Polyester	Choline chloride-Urea	ChCl:Ur = 1:1 to 1:4	DES enabled adsorption/dyeing of anthraquinone dyes onto polyester fabrics (PETFs) under mild ("facile") conditions	[139]
Polyester	Choline chloride-Malonic acid	ChCl:MalAcc=1:1 to 1:4	Anthraquinone dyes exhibited distinct interaction types with different DESs. DES is synthesized from choline chloride, urea, and glycerin as a water-reducing dyeing medium.	[139]
Polyester	Choline chloride-Urea-Glycerol	ChCl:Ur: Gly = 1:1:1	DES enabled anthraquinone dye adsorption onto polyester (PETF) under mild ("facile") conditions.	[140]
Polyester	Choline chloride-Methylurea	ChCl:methUr = 1:1 to 1:4	Dye adsorption occurs only when polyester fabric (PETF)-dye interactions exceed PETF-DES affinity; Anthraquinone dyes exhibit DES-specific binding modes	[139]
Polyester	Choline chloride-Polyethylene glycol	ChCl:PEG = 1:1 to 1:4	Anthraquinone dyes exhibit DES-specific binding modes	[139]
Polyester	Choline chloride-1,4-butanediol	ChCl:Butdiol = 1:1 to 1:4	Anthraquinone dyes exhibit DES-specific binding modes	[139]
Polyester	Choline chloride-Glycerol	ChCl:Gly = 1:1 to 1:4	Anthraquinone dyes exhibit DES-specific binding modes.	[139]

discrete cation and anion), deep eutectic solvents are a mixture of two or more components (containing a variety of anionic and/or cationic species) [69]. Deep eutectic solvents are called designer solvents because by changing their components or their ratio, the physicochemical characteristics can be changed. Choline chloride is commonly used for DES solvent system making; thus, studies started with a choline chloride-based DES system to dissolve the cellulose. For example, in early studies, different cellulosic polymers were evaluated to dissolve in the choline chloride base system of DES. The results of the study revealed that cellulosic polymers used in the study, including sodium carboxymethyl cellulose (CMC), xanthan gum, modified guar gum, and carboxymethyl tamarind, were soluble at a specific moderate temperature ($\sim 65^\circ\text{C}$). Different studies used DES combined with different treatments, such as in a study where cellulose samples were activated by ultrasound-assisted saturated calcium chloride solution. Later on, treatment with DES, composed of choline chloride and urea, showed that cellulose was dissolved about 1.43 wt %. However, on changing the DES component (urea with imidazole), the new DES system exhibited improved solubility (2.48 wt %) of cellulosic materials. Moreover, the solubility was further improved (4.57 wt %) when a third component, named polyethylene glycol (PEG), was added to the DES system [148].

DES systems are pivotal for efficient cellulose dissolution in textile valorization, demanding strategic component selection to overcome cellulose's recalcitrant hydrogen-bonded crystalline structure. The hydrogen bond donor choice critically dictates disruption efficiency, with imidazole-based DES achieving 73 % higher solubility (2.48 wt %) than urea-based systems (1.43 wt %). Synergistic additives like polyethylene glycol (PEG) further enhance penetration, elevating dissolution to 4.57 wt % in ternary ChCl-imidazole-PEG formulations. Complementary pretreatments (e.g., ultrasound-assisted CaCl_2 activation) amplify fiber accessibility, while mild operational temperatures ($\sim 65^\circ\text{C}$) preserve polymer integrity. This component-level tailoring enables sustainable production of regenerated textiles (e.g., lyocell fibers) and functional coatings, positioning DES as a designer solvent for biomass-to-textile circularity.

DES design must be precisely tailored to each textile application's unique demands, as solvent functionality is governed by molecular-level interactions between components and substrates [149]. For dyeing processes, hydrophobic DES (e.g., thymol: menthol) requires non-polar HBD chains to dissolve disperse dyes without dispersants, while fiber etching/modification demands acidic DES (e.g., ChCl-oxalic acid) with proton-donating capacity to disrupt polymer crystallinity [150]. In cellulose dissolution, DES components must strategically target β -glycosidic bonds; imidazole's planar structure outperforms urea in breaking C2–C6/C3–C5 H-bonds due to enhanced π -orbital alignment [151]. This process-specific optimization is non-negotiable: viscosity dictates dye penetration kinetics in cotton, while polarity governs contaminant removal efficiency in wastewater. Neglecting these structure-property-application relationships risks suboptimal performance, as evidenced by the 73 % solubility gap between imidazole-based (2.48 wt %) and urea-based (1.43 wt %) cellulose solvents. Thus, successful DES deployment hinges on three pillars: (1) HBA/HBD selection aligned with bond-breaking mechanisms, (2) molar ratios tuned for viscosity/polarity windows, and (3) process-compatible operating temperatures. This deliberate design paradigm enables DES to replace 23+ conventional chemicals while achieving >50 % energy/water reductions, transforming textile manufacturing from linear to circular economies.

4. Applications of DES

4.1. Nanomaterial synthesis and extraction

DESs demonstrate exceptional nanoparticle solubility, making them uniquely advantageous as extraction media [102,125,152,153]. Among the most widely utilized DES components for such applications are lactic acid, choline chloride, and 1,2-propanediol, as evidenced by their

recurrent use in extraction-focused studies [96,125,154,155]. The unique combination of low toxicity, high solubilizing capacity, and structural tunability allows synthetic DESs to serve as complete drug delivery systems without additives [156]. The structural similarity between lidocaine and capsaicin enables their eutectic mixture to retain the characteristic properties of both amides. This principle has been extended to develop transdermal delivery systems using eutectic combinations of ibuprofen with terpenes, including menthone, 1,8-cineole, d-limonene, and p-cymene [157].

DESs are widely used in the extraction and preparation of nanomaterials [158–161]. Chitin nanoparticles and their derivatives have been used in biomedical applications as they are regarded as good drug-delivery agents in anticancer chemotherapy [162,163]. Similarly, chitin gels have been used in scaffolds for bones and cartilage as well as they have been used in wound healing applications because of their excellent antibacterial, biocompatible, and immunological properties [164–168]. It has been used in many applications, especially in drugs, oils, scaffolds, cancer diagnosis, nanocomposites [169–172], wastewater treatment, oil-water separation and purification [173–175], as well as in beverage and food as an additive in the form of emulsion, foam, and gels [176,177]. However, chitin and its derivative extraction process are not easy because of the higher amount of protein and minerals in all sources of chitin. Acid hydrolysis has been preferred in the extraction and preparation of chitin from its sources over the years. However, various problems have been reported in the utilization of the acid hydrolysis process in chitin extraction because of the acid waste produced with the chitin products. Which is not easy to recycle and can't be reused. Thus, green liquids are used for chitin extraction from its sources with zero waste and reusable solvents. These liquids have replaced the traditional acid, in which ionic liquids were reported to be effective in chitin production and noted to be green. However, the cost-effectiveness of ionic liquids paved the way for cheap, easy preparation, reusable, eco-friendly, and naturally biodegradable deep eutectic solvents [168]. Thus, the dissolution and extraction of α -chitin from various sources (crabs and shrimps) are reported [178]. Deep eutectic solvents containing choline chloride and organic acid components have been used in chitin extraction because of the multiple performances of DESs in a single step, including demineralization and deproteinization. Additionally, deep eutectic solvents have been used in the direct preparation of O-acylated chitin, which is reported to exhibit excellent antibacterial and anti-tumor properties [179]. Similarly, they have been used in the preparation of functional materials of chitin, including chitin nanofibers, chitin nanowhiskers, nanofilms, and chitin hydrogels [180–183]. As compared to ionic liquids, deep eutectic solvents are non-flammable and provided superior characteristics, having low vapor pressure values, and excellent conductive and tunable capabilities [184]. Thus, DESs have potential advantages over ionic liquids as they are easy to prepare, cheap in synthesis production, biodegradable, and nontoxic [185–187]. Applications of DESs in various fields are shown in Fig. 4.

4.2. Dye extraction

Recently, deep eutectic solvents have also been used for dye extraction in various studies as they can provide unique physicochemical interactions with analytes [188–190] and can deliver high selectivity of extraction [190,191]. More than 1 million tons of dyes have been reported to be produced from various industrial wastes annually [192]. Methyl violet (MV) is a type of dye that is soluble in water, methanol, diethylene glycol, and glycol [193]; however, it has been used in the textile, plastic, and food industries [193–195]. Thus, in a recent study, authors have presented a report selecting deep eutectic solvents as green solvents for the successive isolation of MV. The proposed methodology demonstrated significant advantages over various other approaches, offering a simplified, efficient, and environmentally friendly alternative for synthesis [196]. This study employed a choline chloride–decanoic acid DES system for dye extraction. Key analytical

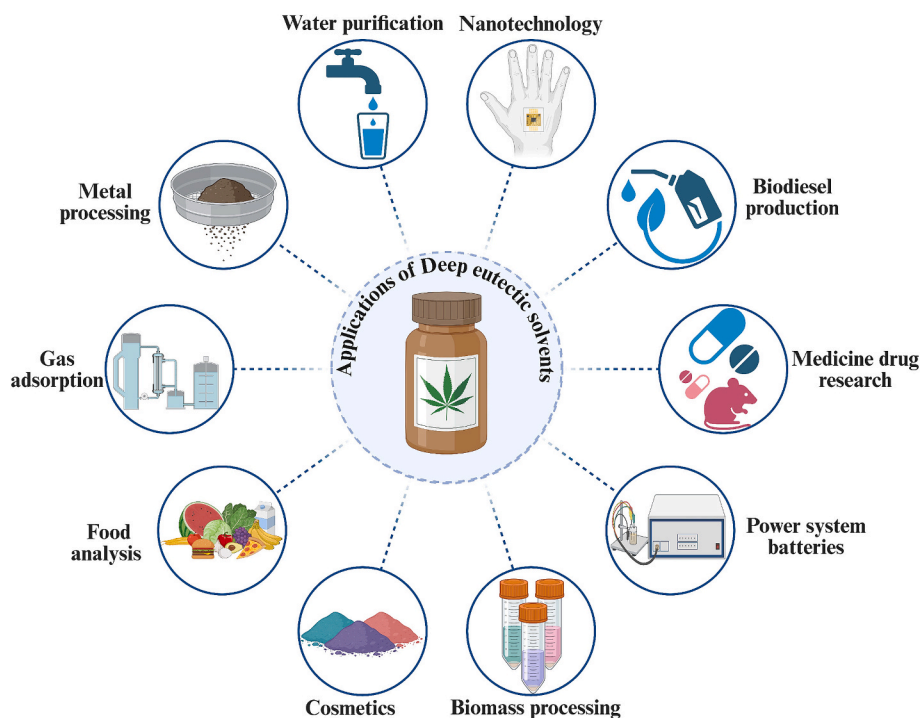


Fig. 4. Applications of deep eutectic solvents

parameters, including pH, DES volume/phase ratio, tetrahydrofuran volume, sonication time, and temperature, were systematically optimized to evaluate their effects on extraction efficiency. Additionally, in another study, they were utilized for neutral red dye isolation because of the low cost, biodegradability, and cheap characteristics of deep eutectic solvents [197]. In this study, choline chloride and phenol (molar ratio 1:2) were used as HBAs and HBDs, respectively, for the extraction of neutral dyes from aqueous media. The presence of dyes in aqueous solutions poses significant environmental challenges, necessitating efficient removal methods. In a study [198], researchers demonstrate the exceptional effectiveness of a DES system comprising tetrabutylammonium chloride and decanoic acid for dye extraction. The system achieved near-quantitative removal, with an efficiency of 99 %, enabling the production of decolorized water. Furthermore, the method proved effective across a broad range of dye concentrations and exhibited reduced solvent consumption. Crucially, the DES also successfully removed mixtures of diverse dyes from solution, highlighting its potential for complex wastewater remediation. A separate study investigated the extraction of anionic azo dyes, specifically Eriochrome Black T (EBT), from aqueous solutions using liquid–liquid microextraction (LLME) with glycolic acid (G) and choline chloride (C) based deep eutectic solvent (DES) systems [199]. Three distinct molar ratios of the hydrogen bond donor (HBD, glycolic acid) and hydrogen bond acceptor (HBA, choline chloride) were evaluated and optimized. The DES formulation comprising choline chloride and glycolic acid was selected based on literature reports of its exceptional solubility for alicyclic compounds. Key operational parameters, including pH, DES dosage, and initial EBT concentration, were systematically optimized to maximize extraction efficiency. Characterization revealed that DES formulations exhibiting higher viscosities (>200 cP) demonstrated significant hydrogen bonding interactions between their constituents. Furthermore, DES solvents possessing densities between 1.31 and 1.41 g cm $^{-3}$, comparable to those of ionic liquids, exhibited superior performance in the dye removal process. Another work reported the anionic (tartrazine and amaranth) and cationic (phenosafranin and methylene blue) dyes extraction by using eight different types of hydrophobic DES systems, where four ionic and four non-ionic types of DES were introduced [200].

The study involves the vortex liquid-liquid microextraction (LLME) technology for dye extraction. The results of the study revealed that ionic and non-ionic hydrophobic DESs exhibited selective removal of anionic and cationic dyes, respectively. Particularly, the extraction efficiency of tartrazine was reached 99.3 % when the DES system containing triethylmethylammonium chloride-thymol was applied. Moreover, the extraction efficiency of phenosafranin was noted to be approximately 99.9 % when the DES system containing decanoic acid-thymol as the extraction agent. The study also showed that the two main factors affecting the extraction process were hydrogen bonding and electrostatic forces. Consequently, the researchers developed an easy-to-use vortex-assisted liquid-liquid microextraction (LLME) technique based on hydrophobic deep eutectic solvents. This method provides excellent dye separation efficiency and superior selectivity, making it an attractive approach for diverse dye extraction applications.

4.3. Battery applications

With the rise of renewables, electricity is now the dominant form of energy requiring storage, driving battery development. Batteries store this energy chemically and convert it back into electrical power. Unlike ionic liquids, deep eutectic solvents are easier to prepare, more cost-effective, and highly biocompatible. These advantages make DESs an excellent choice for the large-scale preparation of nanomaterials used in battery applications. Thus, there have been several studies to prepare nanomaterials for lithium-ion batteries [201–203], fuel cells [204–206], and solar cells [79,207,208] by using deep eutectic solvents. Chiara et al. [207] evaluated DES as an electrolyte medium for dye-sensitized solar cells (DSSCs). DES containing aqueous (40 % w/w water content) choline chloride-based system was investigated thoroughly. By combining this eutectic mixture with an appropriate hydrophilic sensitizer, the team achieved a DSSC with power conversion efficiency comparable to devices using conventional toxic and volatile solvents in the same electrolyte composition. This result suggests significant potential for DESs in enabling a new generation of eco-friendly, nature-inspired, and low-cost solar devices. Moreover, in another study [209], a choline chloride and FeCl $_3$ (ChoCl–FeCl $_3$) based DES system was

introduced as a template and catalyst for graphene nanosheets preparation. *Sargassum tenerrimum* (recovered after liquid juice from a fresh brown seaweed) was used as a raw material, and DES was simply prepared by mixing choline chloride and FeCl_3 constituents. The results of the study revealed that nanosheets were in sheet-like forms and had random orientation. Moreover, the resultant nanosheets show excellent catalytic efficiency in the oxygen reduction reaction even after 30,000 cycles when tested for alkaline fuel cells. In a different study [210], noble metal-based rare earth nanoalloys were evaluated as electrocatalytic materials for possible fuel cell applications. This study employed an effective electrochemical synthesis strategy in a deep eutectic solvent system to produce concave cubic PtLa alloy nanocrystals (CCP_{CNC}) with high-index facets. These nanostructures demonstrated superior electrocatalytic performance for the ethanol oxidation reaction (EOR). Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) morphology revealed that CCP_{CNC} were formed in an ideal size of about 47.5 nm, which were homogeneously electro-deposited on the glassy carbon substrate in DES. Moreover, the results revealed that $\text{Pt}_{10}\text{La}_5$ concave-cubic alloy nanoparticles exhibited improved electrocatalytic efficiency sustainable constancy during EOR,

which shows the excellent performance of as compared of Pt nanoparticles.

Solar cells harness sunlight to produce electricity directly using photovoltaic semiconductors. Compared to alternative solutions, they deliver greater energy production, environmental benefits, and higher conversion efficiency. This has spurred strong research interest in advanced nanomaterials exhibiting unique photoelectric behavior, especially those fabricated with deep eutectic solvents. Due to their accessibility, low cost, and eco-friendly nature, deep eutectic solvents (DESs) are widely used for nanomaterial synthesis in solar cell applications. Additionally, perovskite nanocrystals (PNCs) are widely employed in solar cell technology due to their superior photophysical properties and structural tunability. The superior optoelectronic performance of perovskite nanocrystals (PNCs) has spurred significant research interest for light-emitting diodes (LEDs), solar cells, and photocatalytic applications [211–213]. Leveraging these properties, Lu et al. [214] recently developed a facile, rapid, and solvent-free synthesis strategy for PNCs using NADESs, as shown in Fig. 5a. Their approach combined DL-menthol and thymol (Thy) with eight distinct hydrogen-bond donors (HBDs) in equimolar ratios to formulate the NADES

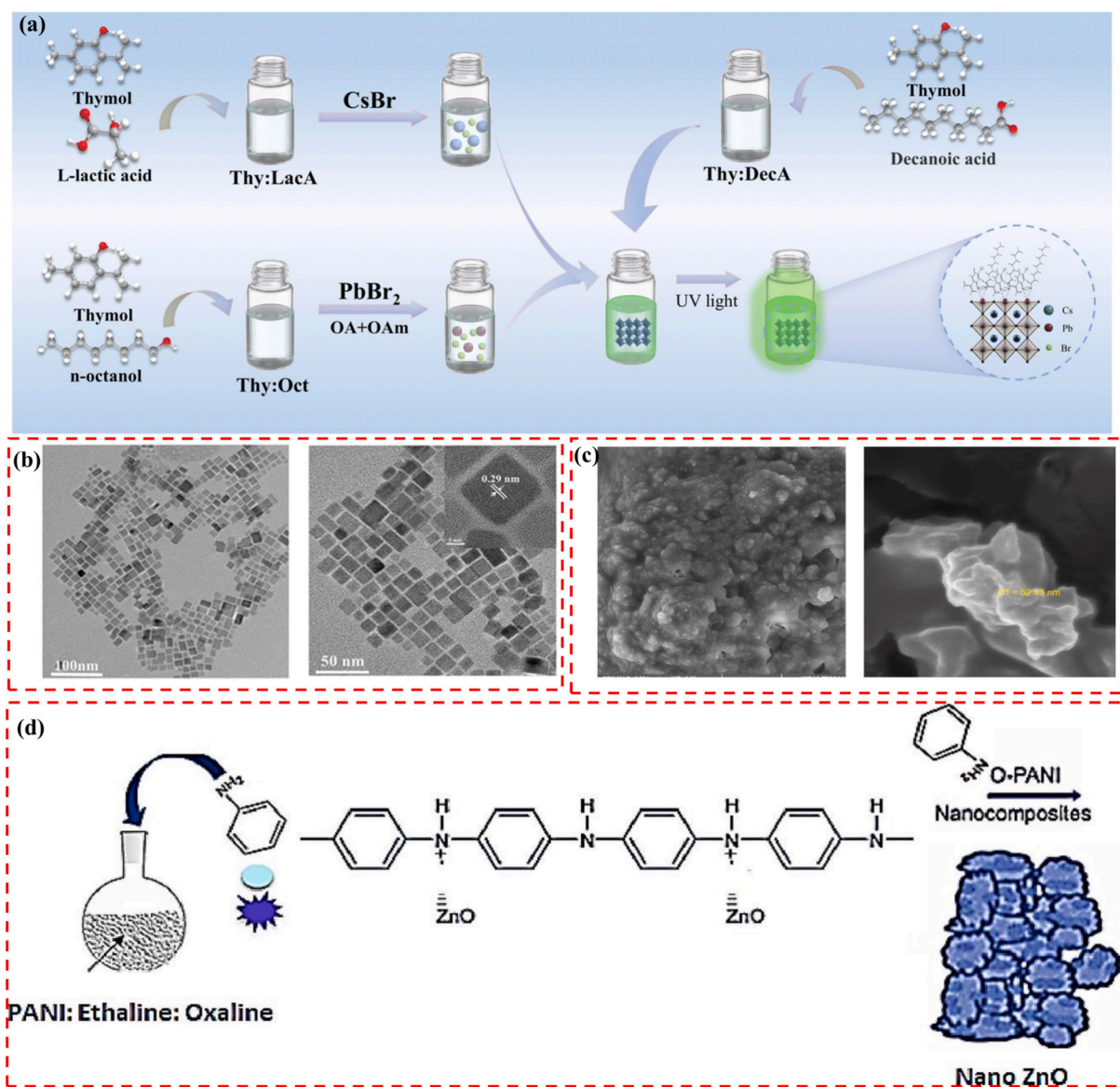


Fig. 5. Schematic illustration of NADES-CsPbBr₃ PNCs (a). TEM morphology of NADES-CSPbBr₃ PNCs (inset shows the corresponding HRTEM) (b) [214], SEM photographs of ZnO nanostructures with 0.1 M aniline (c), and schematic representation of ZnO nanomaterials (d) [215].

medium. The synthesized CsPbBr₃ PNCs achieved a near-unity photoluminescence quantum yield (PLQY) of 96.8 %, narrow emission (FWHM $\approx$ 18.8 nm), and exceptional stability, retaining 82.9 % PL intensity after 70 days.

The as-synthesized CsPbBr₃ PNCs exhibited high photoluminescence quantum yield (PLQY, $\sim$ 96.8 %), narrow full width at half-maximum (FWHM, $\sim$ 18.8 nm), and a high stability that retained 82.9 % of PL intensity after 70 days. Moreover, CsPbBr₃ PNCs prepared by the NADES system exhibited excellent stability and high catalytic performance, as shown in Fig. 5b. Morphological TEM characterization confirmed the cubic structure and uniform dispersion of the NADES-CsPbBr₃ PNCs.

A separate study utilized a deep eutectic solvent system comprising a 1:1 molar ratio of ethaline and oxaline to synthesize uniform zinc oxide (ZnO) nanoparticles [215]. Polyaniline polymer additives facilitated nanoparticle formation, with aniline and water molecules enhancing nucleation kinetics in the DES medium. The ZnO nanoparticles were green-synthesized via digestate extraction of olive leaves in a ternary DES (aniline: ethaline: oxaline). This study established deep eutectic solvent emulsions as effective media for electrochemical synthesis, leveraging their eco-friendly properties and natural abundance as shown in Fig. 5d. Synthesized ZnO nanocrystals exhibited uniform dispersion with 37 nm diameters, while microemulsion-derived nanocomposites displayed distinct morphological structures containing larger (50–100 nm) nanoparticles. Fig. 5c confirms the dense porous morphology of the synthesized ZnO nanoparticles. Their synergistic combination with polyaniline enhanced DES dielectric band gap characteristics, broadening functionality for electrochemical devices, particularly solar energy harvesters and microchemical sensors. Under electrochemical conditions, microemulsion systems enhanced the formation of structured ZnO nanocomposites through synergistic interactions with aniline, resulting in superior electrochemical performance.

Although electrodeposition followed by annealing is a cheap and effective method for synthesizing Cu(In,Ga)Se₂ (CIGSe), however, it faces a significant challenge: achieving controllable gallium deposition from aqueous electrolytes. This difficulty arises from the interference of the competing hydrogen evolution reaction (HER). To achieve energy-efficient deposition control, a deep eutectic solvent was employed for Cu(In,Ga)Se₂ thin film solar cells in a different study [216]. Specifically, a DES composed of choline chloride and urea in a 1:2 molar ratio enabled the single-step electrodeposition of copper, indium, and gallium. The ChCl: U-CuCl₂-InCl₃-GaCl₃ system was analyzed using rotating disk electrode cyclic voltammetry. The results revealed multiple redox responses corresponding to the electrodeposition of various Cu_x(In,Ga)_y intermetallic compounds. Subsequent selenization successfully converted the metallic precursor layers into CIGSe films without Ga segregation. Although the resulting solar cell efficiency reached only 2.7 %, this work establishes a versatile single-step deposition method where precursor morphology is controllable by tuning the solution composition and applying multi-step potentials during growth. Electrodeposition offers high deposition rates and production efficiency. The process requires precise control of parameters such as current, voltage, and temperature to achieve uniform layers with tunable thickness and properties. However, when using deep eutectic solvents for preparing functional materials, a key challenge is their difficult recyclability, because of their preparation from diverse raw materials. The practical application of DESs in batteries is often limited by their hygroscopic nature and difficult recyclability. Addressing these challenges, through the dedicated development of non-hygroscopic and easily recyclable DES formulations, is critical to unlocking their exceptional potential for electrochemical and materials synthesis.

5. Functionalization of textiles by DES

5.1. Cellulosic fibers

Rising environmental concerns and a strong research focus on green chemistry are driving the rapid development of sustainable, non-toxic materials and products [217]. Petro-based textiles such as polyester, nylon, and acrylic fulfill the requirements of fast fashion but pose significant environmental challenges: they persist in the environment due to slow degradation and emit hazardous substances upon combustion [218]. Thus, it is really important to introduce a novel green material and method for the successive and effective surface modification of cellulose-based textile fibers and fabrics, having minimal environmental issues. With the increase in demand for functional fabrics, the modification of textile fabrics has increased recently; that's why superhydrophobic cotton fabrics have been developed, exhibiting excellent potential in various fields of applications because of their superior properties [219–221]. Nevertheless, there are still significant difficulties in the widespread use of superhydrophobic cotton fabrics because of the lower durability of modifying materials and the use of hazardous and toxic chemicals in the finishing process. Generally, there are two methods used for creating a super-hydrophobic surface on cotton fabric: increasing the fabric's surface roughness [222,223] and lowering the fabric's surface energy [122,224].

Thus, in a recent study [225], eco-friendly and economically cheap material DES was synthesized for surface modification of cotton fabrics to obtain hydrophobic properties. The study acknowledged that the cotton fiber surface was etched by using a moderately deep eutectic solvent composed of choline chloride and oxalic acid, excellently improving the surface roughness of cotton fibers. The surface roughness of DES-pretreated cotton fabric is generally increased at specific experimental conditions, and it is easy to modify the fabric surface. A thermoset coating, synthesized from stearic acid-modified epoxidized soybean oil, was then applied to the fabric. This finishing process utilized entirely bio-based substances, as the coating and the deep eutectic solvent were both derived from biological sources. The mild nature of the DES, compared to conventional etchants, preserved the fabric's mechanical strength while simultaneously enhancing its resistance to friction and wear [225]. Fig. 6a shows a schematic illustration of the modification of fabrics and the obtained results of modified cotton samples. The author was able to get the cotton fabric coated with epoxidized soybean oil and stearic acid, and the modified coated fabric exhibited excellent self-cleaning properties, strong superhydrophobic, and super oil-water separation properties as shown in Fig. 6(b–e). Similarly, the cotton fabric surface has been modified by using environmentally friendly choline chloride-based deep eutectic solvents as treatment media instead of traditional solvents. Researchers embedded antibacterial properties into the cotton by applying 3,3',4,4'-benzophenone tetracarboxylic dianhydride (BTDA) through a combined shaking immersion and pad-dry-cure process. This demonstrates that ChCl-based DES provides an eco-friendly, straightforward, and inexpensive pretreatment for producing novel antibacterial cotton [226]. Study results revealed a clear surface modification as compared to ntreated samples after treatments with deep eutectic solvents, as revealed by morphological analysis in Fig. 6f. The modified fabric exhibited excellent hydrophobic properties. This was demonstrated by the formation of flower-like patterns from variously sized liquid droplets, confirming successful hydrophobic finishing (Fig. 6g). Fig. 6h shows the possible antibacterial activity of coated fabrics after etching by deep eutectic solvents.

Two of the most pressing barriers to a sustainable textile industry are its intensive water footprint and reliance on toxic chemicals. According to the World Bank, conventional dyeing is responsible for 20 % of global industrial water pollution, consuming a staggering 5.8 trillion liters of water each year [227,228]. To address its immense water footprint, the textile processing industry must prioritize the development of

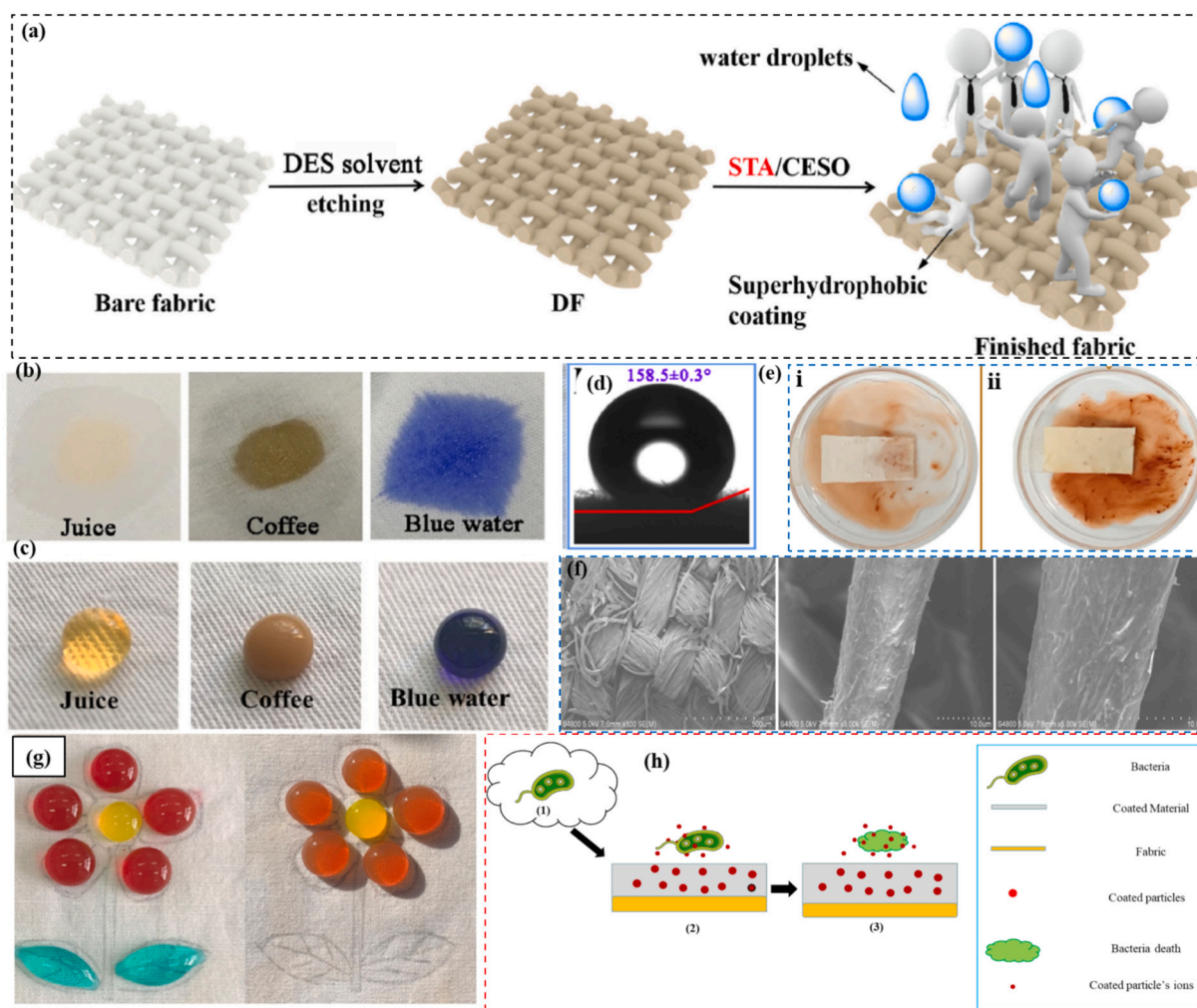


Fig. 6. Schematic illustration of super-hydrophobic cotton fabric preparation by using the DES etching technique (a), different liquid droplets were wetted on the untreated fabric surface (b), and placed on the treated surface with spherical status (c), and water contact angle image of modified cotton fabric (d). The self-cleaning behavior (e) of untreated (i) and modified cotton fabric sample (ii) against dust contaminants, the SEM morphology of treated samples (f), and the photo of flower design with various sizes of a specific liquid droplet on modified sample surface (g) [225]. A proposed schematic diagram of antibacterial activity of coated fabric etched by deep eutectic solvents (h), bacterial attack (1), bacterial adhesion and metal ions binding (2), and bacterial death (3).

innovative, low-water consumption technologies as a core component of its sustainability strategy [229]. Depending on the type of dyes used, around 30 to 50 liters of water are needed per kg of fabric for dyeing. To decrease water usage in the textile sector, researchers have been working on the development of sustainable dyeing processes such as supercritical carbon dioxide, air dye, and plasma processing [228,230]. Thus, most recently, scientists are evaluating solvent dyeing techniques to dye textile products so that water consumption can be minimized. For example, in a recent study [231], cellulose-based textile material cotton dyeing was done by using eutectic solvents combined with curcumin. This study reported an 80 % reduction in water usage and elimination of inorganic salt needs. Solvent dyeing techniques have been used for over a decade to fulfill the need for eco-friendly and low-cost processing. Maximizing this green approach, recent scientific efforts are exploring the application of deep eutectic solvents. Thus, a study was conducted in the year 2019 to utilize an ecologically acceptable solvent in response to such demands [140]. To reduce water usage and environmental risks, glycerine-based eutectic solvent (GES) was synthesized by utilizing choline chloride, urea, and glycerine as a coloring medium. The author's findings imply that using GES as a polyester dyeing medium leads to an environmentally friendly and comparatively cheap technique to be used [140]. In a separate study [232], researchers developed a bioinspired deep eutectic solvent system composed of choline chloride, guanidine,

and phosphoric acid, which was further functionalized with graphene to produce G-DES for cotton fabric flame retardancy applications. The team applied these coatings to cotton substrates and evaluated their performance through standardized flammability testing, including spirit flame tests, limiting oxygen index (LOI) measurements, and vertical flammability tests (VFT). Results demonstrated significant enhancement in fire resistance: DES-treated fabrics withstood open flame for 180 seconds, while G-DES-treated samples resisted combustion for 300 seconds, a dramatic improvement compared to untreated cotton (15 seconds complete burn-through). The coatings achieved LOI values of 39.5 % (DES) and 52.5 % (G-DES), indicating self-extinguishing behavior, while maintaining fabric transparency and biocompatibility. These findings establish both DES and G-DES as promising green alternatives for textile flame-retardant applications.

In line with green chemistry principles, recent studies have explored replacing water-based dyeing systems with deep eutectic solvents for cellulose nanofibers. While conventional methods (e.g., batch or ultrasonic dyeing with reactive dyes) achieve good color yield on CNF [233], they generate significant wastewater containing unfixed dyes and salt, posing environmental risks [234]. In contrast, DES-based dyeing of CNF, conducted without water or auxiliaries, demonstrated a 37 % higher color yield compared to conventional methods, alongside reduced environmental impact. Similarly, the results show that the diffusion and

standard affinity of both types of reactive dyes toward cellulose nano-fibers in the deep eutectic medium were much higher than in the conventional medium.

5.2. Protein-based fibers

Recently, researchers investigated enhancing the color strength of the silk fabric by using a green DES as a swelling agent. Hence, DES was carefully prepared and utilized as an effective swelling agent during the solvent-assisted dyeing of silk fabric samples [235]. DESs were selected for silk fabric modification due to their superior solvent properties, including high proton activity, ionic delocalization, and strong polarization, which make them highly effective for biomass treatment and pretreatment [113]. Similarly, keeping in mind the extensive wastage of water and utilization of hazardous chemicals during the dyeing process of textile material, a new approach has been used recently to dye the woolen fabric by using an acidic deep eutectic solvent in another study [236]. For a better comparison, in this study, conventional aqueous dyeing was also performed using C.I. 249 dye dissolved in water, with acetic acid (4 % o.w.f.) for pH adjustment. Woolen fabrics were dyed at different concentrations, times, and temperatures. Finally, fabric samples were washed with warm water (80 °C) to remove excess dye. The developed dyeing process demonstrated excellent potential for industrial adoption due to its low cost, reduced chemical consumption, and minimal waste production. The dye stability was examined by using UV-Vis absorption curves, which reveal that when the same amount of dye is added, the dye's absorption intensity in the deep eutectic solvent is lower compared to that in the conventional aqueous bath. However, the absorption spectrum of the dye in the deep eutectic solvent is broader. This difference can be attributed to variations in the protonation degree, along with the influence of hydrogen bonding and electrostatic interactions between the dye and the deep eutectic solvent. The findings suggest that the dye exhibited a more uniform and refined dispersion in the DES compared to the conventional aqueous bath, which significantly enhances the dyeing process. Moreover, these results highlight the potential of deep eutectic solvents as an effective medium for wool dyeing applications. Additionally, the results of the study revealed that the material-to-liquor ratio (MLR) was optimized at 1:20 based on the observed trend in the K/S value, which initially increased before declining. Increasing the solvent content promoted dye circulation and minimized aggregation. However, an excessive amount of solvent caused the dye to disperse excessively into the liquor, negatively affecting the process efficiency. Moreover, the study investigated the impact of airtightness on the K/S value of woolen fabric; the dyeing time, temperature, and dye concentration were held constant while varying the airtightness. The results showed that the error margin for woolen fabric dyed in a conventional aqueous bath was significantly higher than that in the deep eutectic solvents. This discrepancy can be attributed to changes in dye concentration in the aqueous bath caused by water loss at elevated temperatures, whereas the dye concentration in the DES system remained stable. Consequently, DES presents a promising alternative to water in the dyeing process. Additionally, the woolen fabric dyed in the deep eutectic solvent exhibited a higher K/S value due to the improved dispersion of dye in the solvent. The solvent's properties facilitate the dyeing mechanism by mediating interactions between the electronegative dye molecules and the wool keratin. The study also demonstrated the high water solubility of the DES, as evidenced by the stabilization of wash water pH (≈ 7) and conductivity (0.85) after the second cycle. These results confirm that any residual solvent is effectively removed after the first wash, ensuring the dyed wool's suitability for industrial apparel applications. Moreover, the study revealed the color fastness performance of dyed woolen fabrics using three different techniques, including rubbing (crock) fastness, wash fastness, and light fastness. The results indicated that dyed fabric achieved high grades in all tests, meeting apparel industry standards. These findings suggest that DES could be a viable, eco-friendly alternative to traditional water-

based dyeing methods. The excellent water-free dyeing of wool was successfully evaluated, possibly due to the interesting structural stability of the wool containing peptide bond, hydrogen bond, and disulfide bond [237,238]. Idris et al. [239] inspected the wool dissolution in choline chloride and oxalic acid deep eutectic solvent and resulted that the solubility was noted approximately as 30 mg g^{-1} (keratin/solvent) for 10h using temperature 130 °C, which shows excellent lower values as compared to ionic liquids, thus they supposed that deep eutectic solvent was not purely active for keratin dissolution. So, the author assumed that the DES effect on wool protein macromolecular structure in the dyeing process can be minimized and adjusted to an acceptable range only by controlling the time and temperature. Deep eutectic solvents can exhibit both acidic and basic properties, but their mechanisms differ from those in aqueous systems. In water, acidity arises from proton (H^+) dissociation (e.g., $\text{HCl} \rightarrow \text{H}^+ + \text{Cl}^-$), while basicity involves hydroxide (OH^-) generation. In contrast, DES acidity often stems from hydrogen bond donor components (e.g., oxalic acid) whose hydrogen atoms become more positively polarized due to strong hydrogen bonding with the hydrogen bond acceptor. This reduces electron density around the HBD's acidic protons, enhancing their acidity. Similarly, DES basicity depends on the HBA's ability to stabilize protons or disrupt hydrogen bonds. These unique interactions explain why DES proton activity cannot be directly compared to aqueous pH scales. Moreover, researchers developed a durable MXene-coated silk fabric for smart thermal management by first pretreating silk with a choline chloride/oxalic acid deep eutectic solvent to enhance adhesion, then coating it with sericin-protected MXene (SSMXene) in a recent study [240]. The resulting fabric achieved strong heating (55.6 °C) and cooling (low 0.24 infrared emissivity), while remaining breathable, washable, and flame-resistant. This DES-based method offers a scalable, eco-friendly way to create high-performance wearable textiles. In detail, the fabric samples were prepared to design SSMXene-coated silk fabric using a three-step route, as shown in Fig. 7a. Silk fabric in degummed form was soaked in a ChCl/OA-based DES system at a specific time and temperature (2 h, 60 °C) in the first step. In this process, the degummed silk fibers were etched to obtain a rough surface, allowing for the application of a robust SSMXene coating in an excellent manner without requiring high-temperature treatment or prolonged immersion in water. Later on, DES pretreated-etched fabric (DES-silk) was immersed in SMXene dispersion at normal temperature and finally dried at 40 °C. This dipping and drying process was revised several times to enhance the SSMXene loading. Because of superior electrical conductivity, low mid-IR emissivity, and excellent flame retardancy of MXene, the designed M-silk fabrics resulted in outstanding electrical heating, passive radiative heating, and fire resistance (Fig. 7b). The etching of silk fibers shows due to the disruption of hydrogen bonds and hydrophobic interactions of silk fibroin by the ChCl/OA DES system, numerous microfibrils were exfoliated, as shown in Fig. 7(c-e). The chemical composition of silk fabric (before and after pretreatment with the DES system) was examined by using the FTIR technique (Fig. 7f), and results revealed that the peaks obtained in FTIR spectra were identical in the same position to those found in the original silk fabric sample, confirming that the intrinsic secondary structures of silk were retained after DES micro-etching. Meanwhile, XRD results confirmed that the inherent crystalline structure of the silk fabrics remained intact following DES micro-etching, which is important to maintain the superior mechanical properties of silk fabric samples, as shown in Fig. 7g.

The tensile strength of the DES-treated silk fabric was maintained at 180.67 N, as shown in Fig. 8i, representing only a 2.34 % decrease compared to the untreated silk fabric (185.00 N). These results confirm that the micro-etching process does not significantly compromise the mechanical properties of the material. To demonstrate practical applicability, M-silk and DES-silk fabric samples (2.0 cm $\times$ 2.0 cm) were adhered directly to bare skin (Fig. 8i). The surface temperature evolution at thermal equilibrium was monitored using an IR thermal imager to assess passive radiative heating performance. As shown in Fig. 7j, the

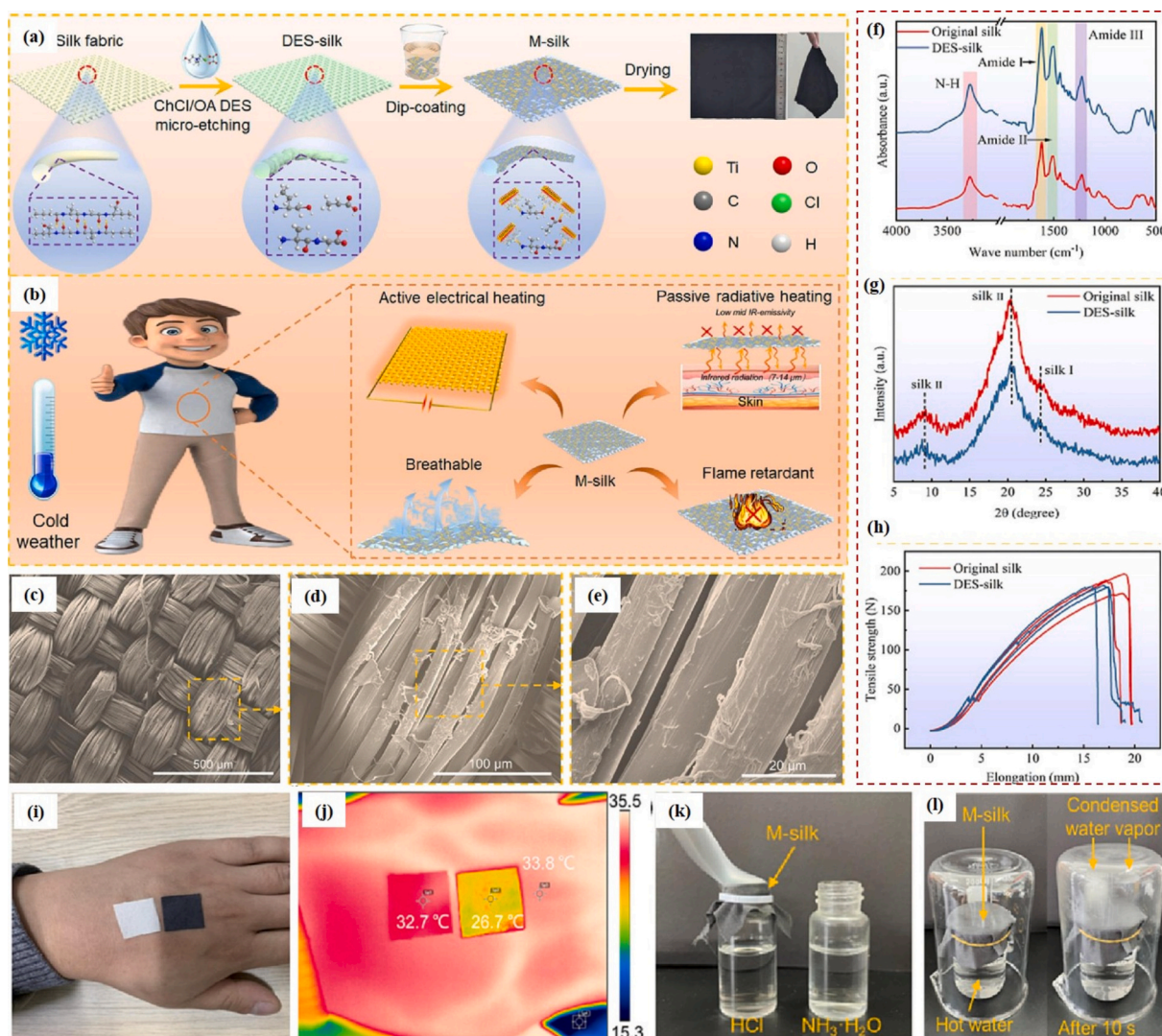


Fig. 7. Fabrication and application of SSMXene-coated silk fabrics, schematic illustration of the SSMXene-coated silk fabrication process (a), the breathable, flame-retardant SSMXene-coated silk fabric enables electrical heating and passive radiative heating, offering potential for personal thermal management in cold environments (b). SEM images of silk fabric samples after pretreated with DES (c–e). FTIR (f), XRD patterns (g), and stress-strain curves of untreated and DES pretreated fabric samples (h). Digital photo (i) and IR image (j) of M-silk and DES-silk attached to the bare skin. White smoke forms as HCl and ammonia diffuse through M-silk, proving its excellent breathability (k). M-silk allows steam from a heated beaker to pass through, forming condensate in a cooler outer beaker (l) [240].

DES-silk reached an equilibrium temperature of 32.7 °C, just 1.1 °C below bare skin temperature (33.8 °C). These results indicate the limited passive warming capability of silk fabric. M-silk maintained high air permeability when treated with DES, ensuring effective gas exchange. Gas diffusion tests (Fig. 7k) revealed unhindered HCl vapor transmission through M-silk, as evidenced by ammonium chloride (NH_4Cl) formation above the sealed vial. The water vapor permeability of the textiles was evaluated using a modified beaker test. A small beaker containing hot water (>80 °C) was sealed with M-silk fabric and subsequently covered with a larger beaker. As evident in Fig. 7l, water vapor diffused through the M-silk membrane and condensed on the inner surface of the outer beaker, confirming the material's effective water vapor transmission properties.

5.3. Synthetic Fibers

In the modern textile industry, polyethylene terephthalate (PET) fibers have emerged as the second most widely used fiber after cotton [241]. Thus, recently, Wang et al. [242] used DES containing constituent choline chloride and oxalic acid to successfully convert the

hydrophobic surface of PET fabric into a hydrophilic one. In this study, the hydrophilic wettability of PET fabric was tremendously improved by implementing physical etching and applying chemical modification by using a eutectic solvent containing components like choline chloride and oxalic acid. On further evaluation of the study, results acknowledged that the polarity of the fabric samples was highly improved, and the surface structure of the PET fabric was changed from hydrophobic to hydrophilic because of DES swelling and chemical effectiveness. Fig. 8a shows the schematic illustration of the process for PET fabric modification by DES. The mechanical properties of treated and untreated fabrics are presented in Fig. 8b(i, ii), the DES-PET-60 sample exhibited a 4.2 % decrease in tensile strength compared to the pure PET fabric (Fig. 8bi), and the DES-treated fabric sample (DES-PET-60) showed a 5.4 % decrease in elongation compared to the pure PET fabric (Fig. 8bii). The results of the study revealed that the pretreated PET fabric's mechanical properties were correlated to the fiber's etching and weight loss. Additionally, the deep eutectic solvent acted excellently only on the surface of the fabric and did not alter its overall structure. The SEM images of pure and treated PET fabrics revealed a clear identification of the importance of DESS. As shown in Fig. 8b, the pure PET fabric was

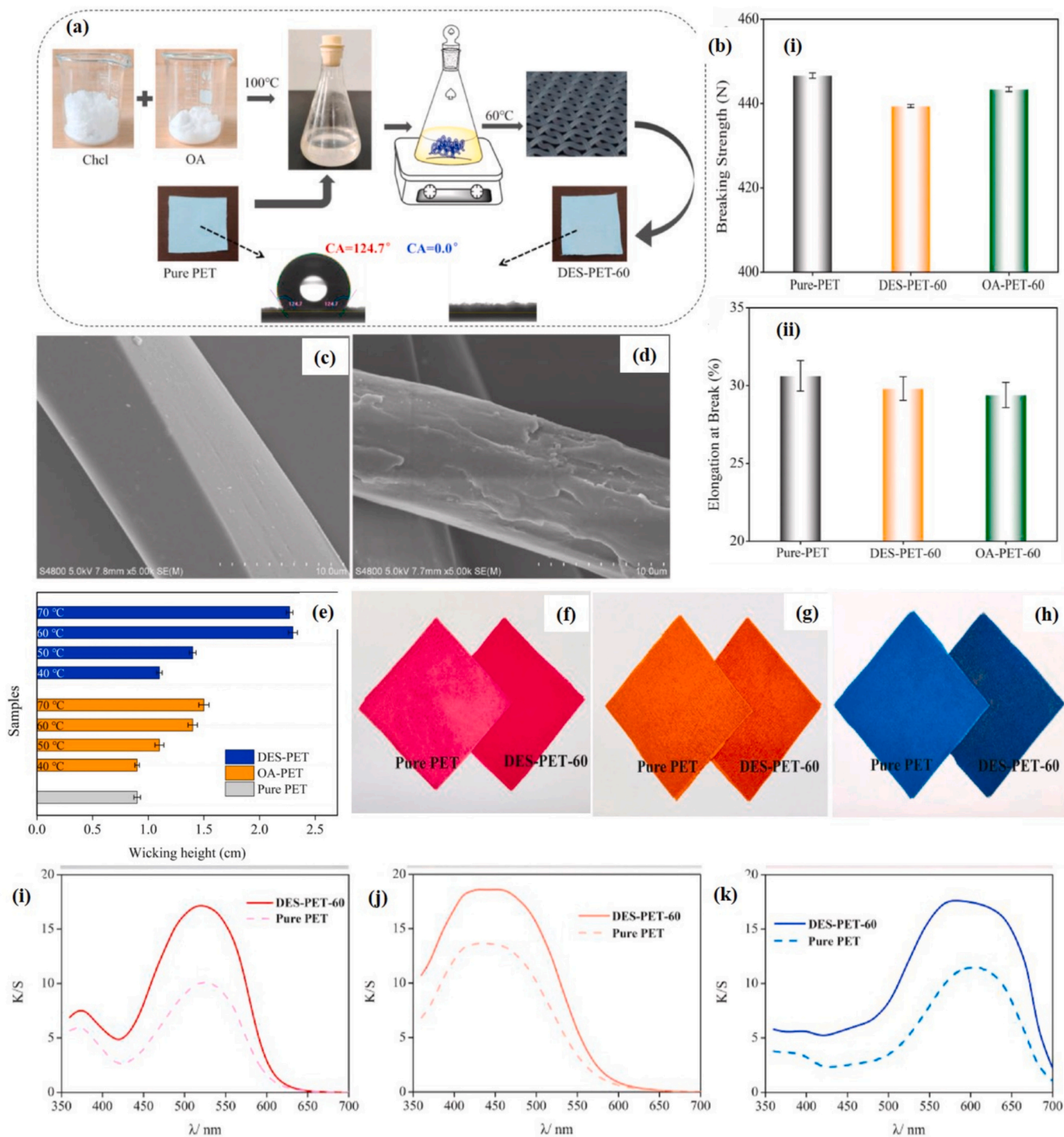


Fig. 8. Schematic illustration of PET fabric modification from hydrophobic to hydrophilic (a), mechanical properties of pristine and modified fabric samples (b) tensile strength (i), and elongation rate of the fabric samples (ii). The SEM morphology of pure PET (c) and pretreated fabric (d) sample (DES-PET-60), wicking heights of different fabric samples (e). The optical images and K/S values of pure PET and DES-PET-60 fabrics dyed with 5BL red (f, i), 4RL yellow (g, j), and HGL blue disperse dyes (h, k) [242].

clean and even, whereas the sample pretreated with DES had an etched surface morphology (Fig. 8c), resulting in higher surface roughness. Moreover, the results of the study revealed that the wicking properties of the fabric samples were influenced by DES pretreatment, as shown in Fig. 8d. The PET fabric samples pretreated with DES solvent or the oxalic acid (OA) solution at different temperatures and specific times (2 h) exhibited high wicking heights as compared to the wicking height of untreated PET fabrics (only 0.9 cm). The results revealed that the DES

solvent or the OA solution improved the hydrophilicity of the PET samples. The study results exhibited that, as compared to pure PET, the DES-PET-60 sample showed a higher K/S value at the maximum absorption wavelength. The optical images of various treated and untreated PET fabric samples are shown in Fig. 8(f–h). Moreover, the K/S values of DES-PET-60 dyed with different liquid disperse dyes such as 5BL red, 4RL yellow, and HGL blue improved significantly (69.5 %, 37.4 %, and 55.1 %, respectively), demonstrating that the color depth of DES-

PET-60 was tremendously increased, as shown in Fig. 8(i–k). As compared to pure PET, the obtained dyeing efficiencies of 5BL red, 4RL yellow, and HGL blue dyes for DES-PET-60 improved by 54.2 %, 30.6 %, and 49.2 %, respectively. These excellent results exhibited that PET fabric samples pretreated with DES solvent (at 60 °C for 2 h) had excellent dyeing properties.

A recent study has demonstrated the efficacy of deep eutectic solvents in enhancing the dyeability of polylactic acid (PLA) fibers [243]. While PLA fibers typically exhibit limited natural dye adsorption due to their high crystallinity and hydrophobic character (imparted by ester and methyl functional groups), DES systems overcome these challenges through multiple mechanisms: (1) partial disruption of crystalline domains to improve dye accessibility, (2) enhanced wettability of the fiber surface, and (3) improved solubility and stabilization of natural dyes in the dye bath. This approach represents a significant improvement over conventional aqueous dyeing systems for PLA textiles. Fabric samples exhibited outstanding multifunctional properties, achieving industry-leading color fastness while demonstrating broad-spectrum antimicrobial efficacy (against *Escherichia coli* and *Staphylococcus aureus*). Similarly, in another study, the mechanism or dyeing process of anthraquinone dyes' adsorption behavior on polyester fabrics (PETFs) in DESs was thoroughly investigated [139]. The polyester fabrics were successfully dyed with anthraquinone dyes by using DES as a solvent. DES facilitated the adsorption of anthraquinone dyes and did not seriously damage or alter the PETF's characteristics. Meanwhile, anthraquinone dyes exhibited a great impact on PETF's characteristics through non-covalent interactions. The results of the study revealed that anthraquinone dyes have various types of interaction with deep eutectic solvents, and PETF adsorption and dyeing can be successfully obtained only when the interaction between PETF and anthraquinones is stronger as compared to that between PETF and deep eutectic solvents. Moreover, the study shows that adsorption and dyeing efficiency were strongly influenced by DES types, the component ratio used in DES (ratio of HBD and HBA), dye concentration, and dyeing time and temperature. This study exhibits an outstanding understanding of the problems encountered with the adsorption and separation of target compounds in deep eutectic solvents. Additionally, instead of traditional toxic solvents for textile dyeing, this study delivers an excellent green alternative for the textile industry in minimizing energy consumption and pollution emissions.

In a different study [244], researchers explored a new eco-friendly way to dye fabrics using natural red pigment from safe bacteria. The study evaluated the different dyeing conditions and resulted in two green solutions: (1) using vitamin-like L-cysteine instead of toxic metal mordants improved color survival during washing, and (2) a natural solvent mixture (DES) made colors last longer in sunlight. The dyed nylon fabrics were reported to protect effectively against harmful bacteria. Most importantly, this process was effective while avoiding harsh chemicals and mixing natural pigment, biological mordant, and green solvent for the first time. These findings demonstrate that we can efficiently dye textile fabrics while protecting human health and the environment. The multifiber fabrics dyed with crude gel prodigiosin pigment, dissolved in a gel-based ChCl/LA (1:2) DES system at pH 1.7, displayed distinct color variations. SEM analysis revealed that both dyed and undyed wool fabrics maintained smooth surface morphologies, with comparable results observed for nylon fabrics. These findings confirm that the dyeing process with crude gel prodigiosin does not alter the structural integrity or surface characteristics of the textiles.

Moreover, the polyester (PET) fabric surface modification and its functional properties were improved by using DES systems containing choline chloride/oxalic acid (ChCl/OA) and chitosan-dissolved ChCl/OA (ChCl/OA-CTS) [245]. The results revealed that the ChCl/OA-based DES system exhibited excellent PET fiber swelling, and the fineness of fibers was comparatively improved (15.92 %). Moreover, SEM morphology shows that the surface roughness of fiber samples was increased, and the surface etching occurred after washing and drying. By

characterization techniques for PET fabric samples, the results showed that the chitosan was loaded on the surface of the PET fiber after ChCl/OA-CTS treatment. Resulting in improving the hydrophilicity and antibacterial properties of PET fabrics (the inhibition rate of *Escherichia coli* and *Staphylococcus aureus* was 92.04 % and 92.16 %, respectively). In a different study, silk fabric samples were modified to increase dyeability by using the DES system containing betaine (Bet) and lactic acid (LA) [246]. Two different types of heating systems, including traditional heating and microwave heating, were used and compared in this study. The study results showed that the tensile strength, crystallinity, and surface roughness properties of the samples were improved. DES pretreatment resulted in a significant increase in surface charge, resulting in a 58-fold increase in dye uptake on the fabric sample, with the dyeing K/S value increasing from 0.075 to 4.071. Additionally, the researchers reported that the breathability of the modified fabric samples was sustained, and the moisture absorption properties of the samples were improved. This research report establishes a novel scientific framework for silk fabric modification using DES systems, demonstrating their dual functionality as both processing media and performance-improving agents.

Moreover, researchers developed an eco-friendly method to rapidly modify PET fabric using a choline chloride/ethylene glycol deep eutectic solvent under microwave irradiation in a different study [247]. When treated for just 60 seconds without additives, the fabric became highly hydrophobic (water contact angle: 135°, absorption time >2000 s). Remarkably, adding only 0.5 % sodium hydroxide completely reversed this effect, creating an instantly water-absorbing hydrophilic surface while maintaining the fabric's structural integrity. Comprehensive characterization (FTIR, SEM) confirmed the surface modification without compromising thermal stability or tensile strength. This simple, green process, requiring only brief microwave exposure, enables precise control of PET's wetting properties for potential applications in performance apparel, medical textiles, and filtration systems, demonstrating DES's versatility for sustainable textile engineering. Table 4 systematically shows DES formulations for textile functionalization, highlighting their role in enhancing key performance metrics.

6. Challenges and Prospects

Deep eutectic solvents are promising green alternatives that are excellent substitutes for traditional solvents because of their superior physicochemical characteristics and eco-friendly nature [256]. However, several critical factors influence DES performance in various areas, including textile-based materials modification and applications. For example, despite their outstanding potential, the lack of techno-economic feasibility evaluations has restricted their large-scale industrial-based applications. Thus, to enable scalable and sustainable DES implementation in textile-based applications, concerted research efforts must address two critical gaps: (i) comprehensive techno-economic assessments and (ii) validation in industrial-scale textile processing [38]. Additionally, the toxicity and cytotoxicity varied according to the specific structure of DES components. Thus, a thorough investigation is necessary to assess the toxicity of DESs before confidently asserting their non-toxic and biodegradable properties for use in textile applications. Similarly, the proper control of experimental conditions is critical. Such as, the addition of a proper molar ratio of HBD and HBA is important for obtaining the required properties of textile fibers and fabrics.

The key problem of deep eutectic solvent application at the industrial level is their relatively high viscosity [257]. Additionally, the viscosity of these solvents not only disturbs the solvent's extraction efficiency because of low mass transfer in the extraction process, but also creates challenges in equipment design, and extra energy is required for agitation and pumping in the extraction process. However, the viscosity of deep eutectic solvents is greatly dependent on the components that make it up; for example, sugar and acid-based deep eutectic solvents have higher viscosity than polyol-based solvents. DES viscosity has also

Table 4
Systematic evaluation of deep eutectic solvents for advanced textile applications

Textile Material	DES Composition	Modification Purpose	Key Findings	Performance Outcomes	References
Silk fabric	choline chloride/oxalic acid	Enhance MXene adhesion, oxidative stability, and thermal management	- SSMXene resists oxidation - DES etching enhances bonding	- Active heating: $\Delta T = 55.6^\circ\text{C}$. - Passive heating: Low mid-IR emissivity - Breathable, flame-retardant - Higher K/S vs. conventional dyeing.	[240]
Wool	Acidic DES	Water-free, recyclable dyeing process	- DES enables dyeing without water, salt, or auxiliaries. - Acts as both dyeing medium and cleaning solvent (reusable $\geq 10\times$) and universal for multiple dyes/DES ligands	- Similar colorfastness/leveling. - Low waste/cost (meets 3R principles) and maintains mechanical properties.	[40]
Nylon (Multifiber tested)	Choline chloride/lactic acid gel-based DES	Sustainable dyeing using bacterial pigment (prodigiosin) with bio-mordants	- Improved washing fastness - DES dyebath enhances light fastness and Prodigiosin + DES shows dual functionality (dyeing + antimicrobial).	- Color fastness: Improved wash (L-Cys) & light (DES) resistance. - Eco-friendly: Replaces synthetic dyes/solvents - Shrinkage: 10 % (DES) vs 8.56 % (NaOCl) vs 32 % (untreated). - Mechanical: Only 6.04 % breaking load loss (vs 24.86 % with NaOCl). - Improved whiteness & lower yellowness. - Water/effluent reduction; DES reusable.	[244]
Wool	Reline (ChCl:Urea, 1:2)	Chlorine-free anti-felting finishing	- DES replaces NaOCl, reducing toxic effluent. - Preserves fiber integrity vs. chlorination.	- Improved whiteness & lower yellowness. - Water/effluent reduction; DES reusable. - Flame resistance: 300s resistance (G-DES) vs 15s (control). - LOI: 52.5 % (G-DES) vs 39.5 % (DES). - Low smoke emission. - Decolorization: 89.4 % (single-step), 98.2 % (two-step). - Reusability: Consistent performance after multiple cycles. - Scope: Effective for 9 diverse PET textile dyes. - Dyeability: Comparable color depth at 70°C (25.5 % energy savings). - Morphology: Reduced crystallinity; enhanced dye uptake. - Dye uptake: 20–30 % increase compared to conventional methods. - Eco-impact: 50 % less water, no salt used. - Reusability: Retains swelling efficacy over more than 5 cycles. - Quality: Maintains tensile strength. - Dyeing Quality: Higher K/S values & improved rubbing fastness. - Process Flexibility: Effective at lower temperatures - Eco-Advantage: Reduced wastewater toxicity. - Conductivity: $5.5\ \Omega\cdot\text{sq}^{-1}$ - EMI Shielding: 34.2 dB (X-band). - Heating: 66.8°C at 5V. - Durability: >50 wash cycles. - Eco-Features: Biodegradable, flame-retardant. - Yield: 10.2 % 5-HMF (vs. $<5\%$ for other DESs). - Sustainability: No toxic catalysts; DES recyclability implied. - Cost: Lower energy input vs. acid hydrolysis. - Quality: HPLC-confirmed product purity.	[248]
Cotton	ChCl/Guanidine/ H_3PO_4 (G-DES: Graphene-enhanced)	Flame-retardant functionalization	- Bioinspired DES synthesis with graphene (G-DES). - Transparent flame retardant preserves fabric color. - Synergistic graphene effect improves performance		[232]
PET (polyester)	Menthol:Oleic Acid (Men: OleA)	Decolorization of glycolysis solution for PET recycling	- Hydrophobic DES selectively extracts dyes - Follows pseudo-second-order kinetics.		[249]
PLA (Polylactic Acid)	Natural DES (NaDES)	Low-temperature dyeability enhancement & hydrolysis resistance	- NaDES reduces PLA crystallinity, enabling dye diffusion. - Creates rougher surface/looser structure for deeper coloration. - Energy-efficient process.		[250]
Cotton	K_2CO_3 -Glyceryl DES	Water/salt-reduced dyeing via fiber swelling	- DES disrupts cellulose H-bonds, increasing amorphous regions (59.5 % Sw %). - Creates porous fiber structure for enhanced dye diffusion. - Fully recyclable DES system.		[251]
Polyester	ChCl: Ethylene Glycol (1:2)	Dispersant-free dyeing of dispersed dyes	- DES dissolves Disperse Blue without dispersants. - Forms stable liquid dye solutions. - Temperature-dependent dissolution kinetics.		[135]
PLA	Choline chloride/oxalic acid	Green e-textile fabrication with oxidation-resistant MXene	- DES etching enhances MXene@SSCNT adhesion via H-bonding. - SSCNT co-assembly prevents MXene oxidation. - Biomimetic leaf-like conductive networks formed.		[252]
Waste Cotton Fabrics (WCFs)	Choline chloride (ChCl) and p-toluenesulfonic acid (p-TSA)	Catalytic conversion of WCFs to 5-HMF (biobased platform chemical)	- ChCl/p-TSA DES achieves the highest 5-HMF yield (10.2 %) without added catalysts. - Selective degradation of cellulose to 5-HMF. - Operates at mild conditions (100°C, 90 min).		[253]

(continued on next page)

Table 4 (continued)

Textile Material	DES Composition	Modification Purpose	Key Findings	Performance Outcomes	References
Silk	Choline chloride and urea	Low-temperature dyeing with enhanced color strength	• DES swells silk better than water (quantify % if data exists). • Maintains conventional fastness properties.	• Energy Savings: 10 °C lower vs conventional dyeing. • Time Reduction: 5-10 min faster. • Color Strength: Higher K/S values. • Fastness: Equal wash/light/rubbing scores to aqueous dyeing. • Durability: Withstands 50+ washes (AATCC-61).	[235]
Cotton	Urea-ChCl DES	Antibacterial functionalization	• ChCl enhances pre-UV antibacterial activity. • Process combines pad-dry-cure with immersion for uniform treatment.	• Safety: Eliminates organic solvents. • Quality: Maintains 85-90 % tensile strength. • Dyeing Quality: Higher K/S values vs conventional.	[226]
Polyester	Betaine-based NADES (70 %) + Water (30 %)	Carrier/dispersant-free dyeing	• NADES replaces toxic auxiliaries. • Maintains dye bath pH 4 without acetic acid. • Water content reduced by 70 %.	• Fabric Integrity: 100 % tensile strength retention. • Eco-Impact: Zero auxiliary chemicals; 70 % less wastewater.	[254]
Bamboo Fiber	Chlorocholine Chloride/Urea	Fiber softening & antibacterial functionalization	• Selective removal of hemicellulose/lignin (DS = 0.12). • Fiber linear density reduced by 36 % (22.46 → 14.29 tex). • Inherent antibacterial properties achieved. • Dual physical etching & chemical activation.	• Spinnability: 40 % finer fibers (better textile processability). • Antibacterial: 75.5 % (<i>E. coli</i>) & 72.7 % (<i>S. aureus</i>) inhibition. • Sustainability: Replaces traditional alkali boiling.	[255]
PLA Filament	Chlorocholine/Oxalic Acid	Low-temperature dyeing via surface reconstruction	• Increased surface roughness/chemical activity. • Synergistic effect enables 20 °C lower dyeing.	• Dyeing Efficiency: Equal K/S at 90 °C vs 110 °C conventional. • Energy Savings: 18–22 % reduction in thermal energy.	[138]

been reported as a function of temperature and water content; there, the viscosity of these solvents can be easily lowered by setting the preparation process at a high temperature or adding water to the experimental system [1].

Moreover, despite the demonstrated efficacy of deep eutectic solvents in textile dyeing and modification, critical gaps hinder their industrial adoption. Primarily, there is a lack of systematic evaluation of long-term durability, particularly washing fastness (for 50+ cycles) and mechanical properties under repeated laundering, which are essential for commercial viability. The broader implications of DES integration across textile manufacturing processes, including pre-treatment (e.g., desizing, scouring), downstream applications (e.g., optical brightening, printing), and interactions with auxiliary chemicals, remain critically underexplored, posing potential risks to production efficiency and consistency. To transition DES from lab-scale innovation to industry-ready solutions, future research must prioritize comprehensive durability testing, process integration studies, and lifecycle assessments to validate environmental claims, while fostering industry-academia collaboration to address standardization and pilot-scale implementation barriers.

7. Conclusions

This review article demonstrates that deep eutectic solvents exhibit excellent potential for textile-based applications. Over the past decade, numerous studies have explored hydrophilic/hydrophobic DES systems for fiber and fabric modification, positioning them for a transformative future in the textile industry. DES derived from biocompatible sources, such as guanidine, choline chloride, and phosphoric acid, has shown promise in enhancing flame retardancy, antibacterial properties, and dyeability of textiles. Functionalization of DES with other chemicals,

such as graphene to produce G-DES, has further expanded its utility. For instance, DES- and G-DES-coated cotton fabrics exhibit exceptional flame-retardant performance. Beyond modification, DES also excels in environmental remediation, particularly in dye separation and extraction. For example, reactive dyes like Reactive Red 195A, while providing reliable color fastness, are highly toxic to marine ecosystems and pose carcinogenic, mutagenic, and respiratory risks. Recent studies highlight DES as an effective agent for removing such dyes (e.g., via the ELLME method) from textile wastewater, offering a sustainable alternative to conventional treatments. These bioderived DES and G-DES materials are not only simple to prepare and scalable for bulk production but also versatile for applications ranging from flame-resistant and antibacterial textiles to hydrophobic/hydrophilic coatings and pollutant extraction. Their multi-functionality and eco-friendly nature underscore their potential to revolutionize both textile engineering and environmental sustainability.

CRediT authorship contribution statement

Amjad Farooq: Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Xingang Li:** Writing – review & editing, Formal analysis. **Gangwei Pan:** Writing – review & editing, Formal analysis. **Qixia Liu:** Writing – review & editing, Supervision, Investigation. **Feiyan Wang:** Writing – review & editing, Funding acquisition. **Shenyu Chen:** Writing – review & editing, Investigation, Formal analysis. **Guiyuan Zhao:** Writing – review & editing, Investigation. **Fiaz Hussain:** Writing – review & editing, Supervision, Investigation.

Consent for publication

Approval.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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