

A Review of Chitin Solvents and Their Dissolution Mechanisms

Zhong Yi, Cai Jie, Zhang Li-Na

Cite this article as:

Zhong Yi, Cai Jie, Zhang Li-Na. A Review of Chitin Solvents and Their Dissolution Mechanisms[J]. *Chinese J. Polym. Sci.*, 2020, 38(10): 1047-1060. doi: 10.1007/s10118-020-2459-x

View online: <https://doi.org/10.1007/s10118-020-2459-x>

Articles you may be interested in

[Dissolution, Hydrolysis and Crystallization Behavior of Polyamide 6 in Superheated Water](#)

Chinese J. Polym. Sci. 2015, 33(9): 1334 <https://doi.org/10.1007/s10118-015-1682-3>

[The Influence of Chitin Nanocrystals on Structural Evolution of Ultra-high Molecular Weight Polyethylene/Chitin Nanocrystal Fibers in Hot-drawing Process](#)

Chinese J. Polym. Sci. 2016, 34(11): 1373 <https://doi.org/10.1007/s10118-016-1843-z>

[Aggregation Behavior of Cyclic Rod-Coil Diblock Copolymers in Selective Solvents](#)

Chinese J. Polym. Sci. 2016, 34(4): 420 <https://doi.org/10.1007/s10118-016-1763-y>

[天然聚多糖的溶解机理及溶液性质](#)

Dissolution Mechanism and Solution Properties of Natural Polysaccharides

高分子学报. 2017(9): 1426 <https://doi.org/10.11777/j.issn1000-3304.2017.17108>

[氢键复合膜在酸性溶剂中溶解研究](#)

Disassociation of Hydrogen-bonded Polymer Complex Thin Films in Acidic Solvents

高分子学报. 2015(7): 786 <https://doi.org/10.11777/j.issn1000-3304.2015.14432>

[均相条件下甲壳素基高吸水树脂的制备及性能研究](#)

PREPARATION AND PROPERTIES OF CHITIN-BASED SUPERABSORBENT POLYMERS UNDER HOMOGENEOUS CONDITIONS

高分子学报. 2013(7): 915 <https://doi.org/10.3724/SP.J.1105.2013.12312>

A Review of Chitin Solvents and Their Dissolution Mechanisms

Yi Zhong^a, Jie Cai^{a,b,c*}, and Li-Na Zhang^{a,b}^a College of Chemistry & Molecule Sciences, Wuhan University, Wuhan 430072, China^b Hubei Engineering Center of Natural Polymer-based Medical Materials, Wuhan University, Wuhan 430072, China^c Research Institute of Shenzhen, Wuhan University, Shenzhen 518057, China

Abstract Chitin is an abundant natural nitrogen-containing biopolymer with great application potential in materials, environment, energy, and health. However, the structure characteristics and processing technologies have required intense research in related applications. In particular, there have been great efforts to developing solvents for chitin, and the results so far are quite encouraging. This review summarizes the main solvent systems used for chitin, namely the aqueous solvent systems (mineral acids, inorganic salt aqueous solutions, alkali aqueous solutions) and non-aqueous ones (LiCl-dimethylacetamide solvents, CaCl₂·2H₂O saturated methanol, ionic liquids, deep eutectic solvents, and protic organic solvents). The solvent properties, dissolution methods, and solution properties are discussed in detail. Special attention is paid to the dissolution mechanism in each system. This review can provide a reference for understanding the dissolution behavior of chitin and finding suitable solvents for it.

Keywords Chitin; Solvents; Dissolution mechanism; Hydrogen bonding

Citation: Zhong, Y.; Cai, J.; Zhang, L. N. A review of chitin solvents and their dissolution mechanisms. *Chinese J. Polym. Sci.* 2020, 38, 1047–1060.

INTRODUCTION

Chitin, which is composed of β -(1-4)-linked 2-acetamido-2-deoxy-D-glucose, is the most abundant biopolymer after cellulose (Fig. 1).^[1] It can be found in crustaceans, mollusks, algae, fungi, and insects.^[2,3] The annual production of crustaceans and mollusks around the world is about 7.86 million and 17.14 million tonnes, respectively, and most of it takes place in Asia (7.06 and 15.84 million tonnes).^[4] The discovery of chitin dates from 1799, when Hatchett decalcified shells of crabs, lobsters, prawns, and crayfish with mineral acids.^[5] In 1963, it was determined that crystalline chitin exists in three distinct forms, the α -, β -, and γ -form;^[6] and the crystalline structures of α - and β -chitin were refined in 1980.^[7] Recently, more accurate crystalline structures (1 Å resolution) of α -chitin^[8] and β -chitin^[9] and their hydrogen bonding network structures were determined (Fig. 2).^[8,10] From the perspective of sustainable chemistry and marine economy, the exploitation of chitin as a high-value material has attracted growing interest^[1,11–15] due to its good biological function, biocompatibility, and biodegradability.^[5,16]

In the area of advanced materials, chitin is typically used to fabricate chitin nanocrystals, chitin nanofibers, chitin derivatives, and other chitin-based materials (such as chitin films, hydrogels, aerogels, fibers, and microspheres).^[3,14,17–20] For instance, by adopting a “top-down” strategy, chitin nanofibers

and chitin nanocrystals can be prepared by ultrasonic, grinding, and homogenization techniques, aided by chemical pre-treatments such as acid hydrolysis,^[21] 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO)-mediated oxidation,^[22,23] partial deacetylation,^[24] and alkali deprotonation.^[25] Chitin derivatives can be prepared by chemical modification, including deacetylation, acylation, tosylation, and alkylation under heterogeneous reaction conditions.^[26] The most important area is the solution processing of chitin, where chitin nanofibers and chitin nanosheets may be prepared via a “bottom-up” approach, and homogeneous chemical modification could proceed with higher efficiency and uniformity.^[27,28] Besides, solution processing is more suitable for the large-scale fabrication of products with desired shapes such as films,^[29–32] fibers,^[33,34] gels,^[17,35,36] microspheres,^[37–39] and sponges.^[19,40]

Unfortunately, the high crystallinity and abundant hydrogen bonding network of chitin make it insoluble in most common solvents, and thus great efforts have been made to discover suitable solvent systems. The typical solvents developed for chitin are listed in Fig. 3, and the solubilities of chitin in representative solvents are given in Table 1. These solvents can be divided into aqueous and non-aqueous types, and further classified into mineral acid, inorganic salt aqueous solvent, alkali aqueous solvent, salt/organic solvent, ionic liquids (ILs), deep eutectic solvent (DES), and protic organic solvent. The history of developing chitin solvents is inspiring, and many of these systems are ingenious. This review discusses representative solvent systems in detail, with a focus on the solution properties and dissolution mechanism of each system.

* Corresponding author, E-mail: caijie@whu.edu.cn

Special Issue: Bio-based Polymers

Received April 17, 2020; Accepted May 18, 2020; Published online July 24, 2020

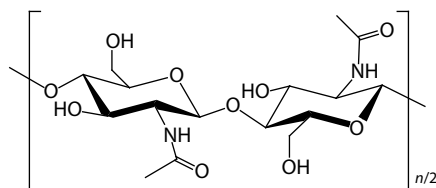


Fig. 1 Molecular structure of chitin, n is the degree of polymerization.

AQUEOUS SOLVENTS

Mineral Acids

The dissolution of chitin in mineral acids was first reported in 1926, when Knecht and Hibbert mentioned that the chitin films could be prepared by precipitating chitin from a cold concentrated hydrochloric acid solution.^[41] Clark and Smith found that chitin could be dissolved in hydrochloric acid when the molar concentration reached 8.5 mol/L, and a much higher molar concentration was needed for sulfuric acid.^[42] The decreased chain length and enhanced degree of deacetylation in chitin dissolution were suggested to increase the solubility of chitin and hinder its precipitation. Meyer and Wehrli found that chitin can be dissolved in various mineral acids (hydrochloric, sulfuric, phosphoric, and nitric acids).^[43] Hackman reported that chitin could be dissolved in concentrated mineral acids such as 10 mol/L hydrochloric acid, 10.5 mol/L sulfuric acid, and 85 wt% phosphoric acid (~15 mol/L) aqueous solutions.^[44] Nagasawa and co-authors found that chitin can be readily dissolved in cold concentrated sulfuric acid through stirring at -5°C , and subsequent storage of the solution for 2 h resulted in the depolymerization and sulfation of chitin.^[45] It is worth noting that the hydrolysis rate of chitin in phosphoric acid is slower than in other mineral acids, making it a suitable solvent at that time. Vincendon found that concentrated phosphoric acid can readily dissolve chitin within 20 min at room temperature under vigorous stirring.^[46] The ^{13}C -NMR spectra of 1 wt% chitin/85 wt% H_3PO_4 aqueous solution are shown in Fig. 4(a), and the chemical shifts of chitin are listed in Table 2. The presence of *N*-acetyl

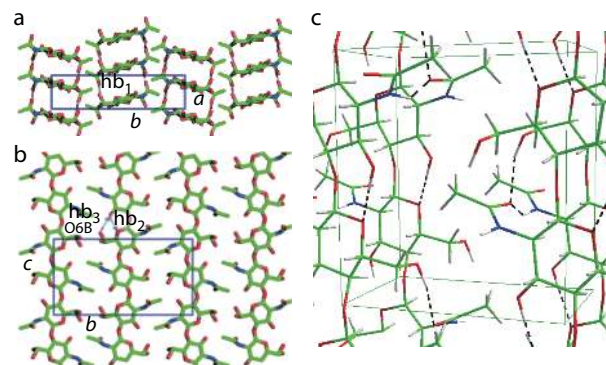


Fig. 2 Crystalline structure of α -chitin and β -chitin. Views perpendicular to the (a) ab - and (b) bc - planes of the α -chitin structure at 100 K (Reproduced with permission from Ref. [8]; Copyright (2009) American Chemical Society); (c) Final hydrogen bonding model of anhydrous β -chitin. The unit cell edges and hydrogen bonds are denoted by solid line and dotted lines, respectively (Reproduced with permission from Ref. [10]; Copyright (2012) American Chemical Society).

signals indicates that after dissolution at room temperature for 12 h in phosphoric acid, no or few *N*-acetyl groups were cleaved. Notably, the viscosity of the solution started to decrease after dissolution, suggesting a continuous decrease in the molecular weight of chitin (Fig. 4b). If the solutions were kept at room temperature for less than 5 h, the main chemical modification was only a small increase in the phosphorus content from 0.08 wt% to 0.17 wt%, which mainly arises from the esterification of the anomeric end-chain (Fig. 4c).^[46] Wu and co-authors found the optimal ratio to dissolve chitin is 3:50 water/85 wt% phosphoric acid (V/V), and the maximum chitin solubility is 4% (W/V).^[47] The degree of *N*-acetylation decreased from 91% in native chitin to 77%–87% in regenerated chitin, suggesting slight deacetylation in the dissolution process. The storage temperature also has a significant effect on the morphology of regenerated chitin, transforming chitin nanofibers with a diameter around 25 nm to large aggregates consisting of short

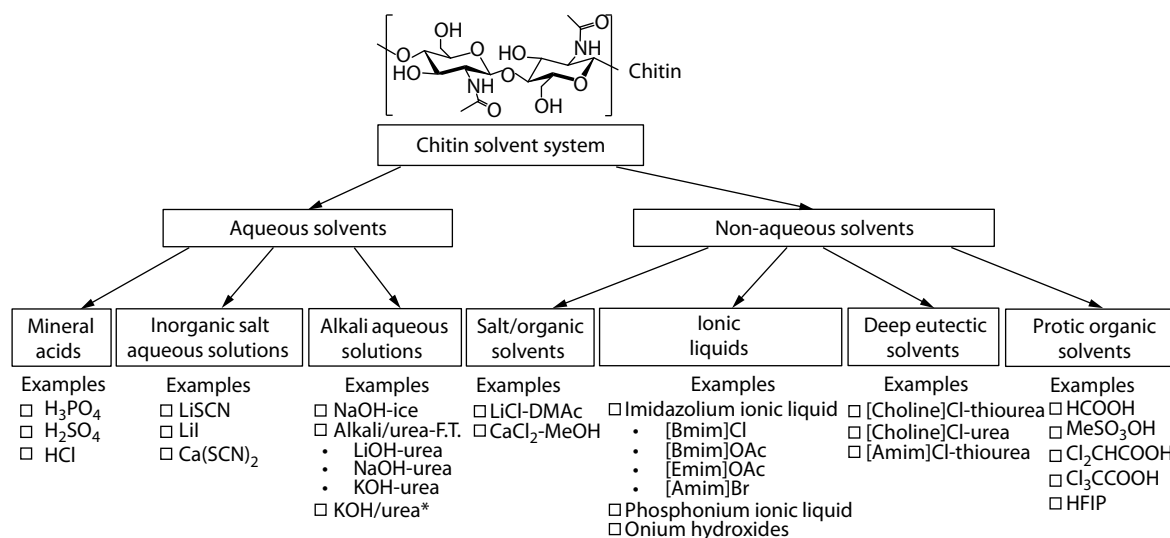


Fig. 3 Classification of currently available chitin solvents. F.T. denotes the freeze-thaw procedure. *KOH/urea can dissolve chitin without freeze-thaw at certain concentrations. HFIP: hexafluoroisopropanol.

Table 1 Solubility of different types of chitin in various solvents.

Solvent	Chitin type	Dissolution procedure	Solubility	Ref.
H ₃ PO ₄	Purified crab chitin	Room temperature for 40 min	3.0% (W/V)	[46]
LiSCN	Purified chitin	Fresh saturated LiSCN aqueous solution	3.0 wt%	[50]
NaOH-ice	Purified chitin	NaOH at 40% (W/W) at 4 °C for 72 h, then mixed with finely crushed ice	0.225% (W/V)	[54]
NaOH/urea aq.	Purified crab chitin	Freeze at –20 °C and stir twice over 36 h	2.0 wt%	[60]
NaOH/urea aq.	Purified crab chitin	Freeze at –20 °C overnight, then thaw at 5 °C	8.0 wt%	[61]
KOH/urea aq.	Purified shrimp chitin	Stir at –30 °C from 10 min to 2 h	9.0 wt%	[31]
LiCl/DMAc	Purified chitin	Stir at 20 °C	2.0 wt%	[50]
CaCl ₂ /methanol	Purified chitin	Reflux for several hours with stirring	2.0 wt%	[80]
[Bmim]Cl	Pure chitin	Heat at 110 °C under an inert atmosphere	10.0 wt%	[90]
[Bmim]OAc	Purified crab chitin	Heat at 100 °C	4.0 wt%	[91]
[Amim]Br	Purified crab chitin	At 100 °C for 48 h under argon atmosphere	5.0 wt%	[92]
[Emim]OAc	Shrimp shells	Heat in oil bath at 100 °C in air for 19 h	4.0 wt%	[93]
[Amim]Cl	Purified chitin	Below 45 °C under argon atmosphere	0.5 wt%	[95]
[Choline]Cl/urea	Purified crab chitin	Heat at 100 °C for 10 h	6.0 wt%	[112]
[Choline]Cl/thiourea	Purified crab chitin	Heat at 100 °C for 6 h	9.0 wt%	[112]
[Amim]Cl/thiourea	Purified crab chitin	Room temperature for 24 h and then 100 °C for 24 h	5.0 wt%	[114]
HFIP	Depolymerized α -chitin powder	Room temperature	6.0 wt%	[119]

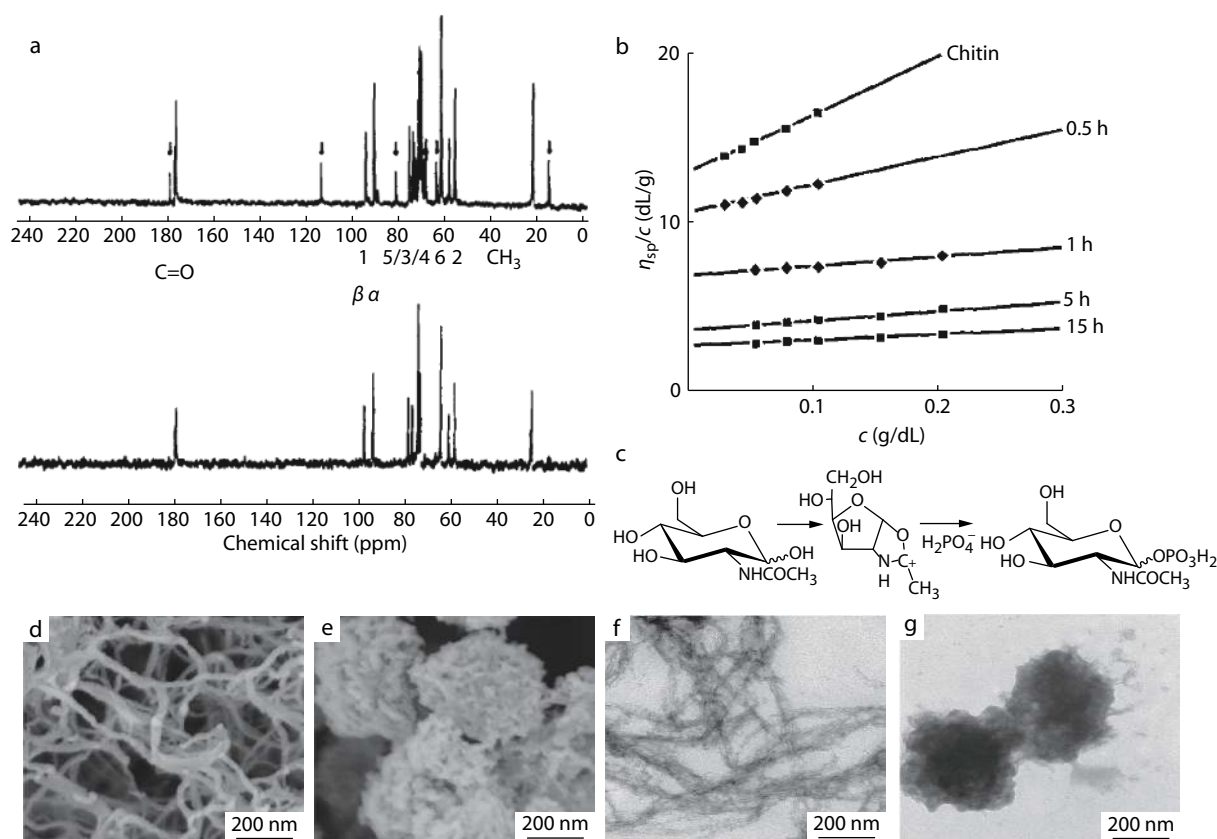


Fig. 4 (a) 100 MHz ¹³C-NMR spectra of chitin (1%) in 85 wt% phosphoric acid solution at room temperature after 12 h (bottom) and 1 week (top); (b) Time-dependent change in the intrinsic viscosity of regenerated chitin in phosphoric acid (solvent: 5% LiCl/DMAc); (c) Scheme of the depolymerization process of chitin in phosphoric acid (Reproduced with permission from Ref. [46]; Copyright (1997) Elsevier). SEM images of regenerated chitin after (d) 12 h at 5 °C and (e) 0.5 h at 50 °C; TEM images of regenerated chitin after (f) 12 h at 5 °C and (g) 0.5 h at 50 °C (Reproduced with permission from Ref. [47]; Copyright (2016) Springer).

chitin nanofibers (Figs. 4d–4g).

Inorganic Salt Aqueous Solutions

The utilization of inorganic salt aqueous solutions to dissolve chitin can be traced to the 1927 work by Weimarn,^[48] who had previously worked on the dissolution of cellulose in inorganic

salt aqueous solutions.^[49] Other polymers like chitin, fibroin, casein, fibrin, and keratin have also been proposed to dissolve or swell in the aqueous solutions of certain inorganic salts that are capable of strong hydration,^[48] such as LiSCN, LiI, LiBr, LiCl, Ca(SCN)₂, CaI₂, CaBr₂, CaCl₂, and Ca(NO₃)₂. The ability to dissolve or swell chitin is ranked in the order of LiSCN > Ca(SCN)₂ > CaI₂ >

Table 2 ^{13}C -NMR chemical shifts of chitin in various solutions.

Solvent	Chemical shift (ppm)								Ref.
	C1	C2	C3	C4	C5	C6	C=O	CH ₃	
H ₃ PO ₄	99.8	55.5	71.5	78.0	73.6	60.0	178.0	21.0	[46]
LiSCN	103.8	58.3	74.8	80.7	74.8	61.7	–	–	[50]
LiOH/urea/ D ₂ O	100.6	55.3	71.7	78.9	75.3	59.8	173.8	21.5	[64]
NaOH/urea/ D ₂ O	100.6	55.3	71.7	78.7	75.7	59.8	173.8	21.7	[64]
KOH/urea/ D ₂ O	100.5	55.3	71.7	78.7	75.7	59.8	173.8	21.8	[64]
LiCl/DMAc	102.1	55.7	74.5	80.5	76.2	59.1	–	–	[50]

$\text{CaBr}_2 > \text{CaCl}_2$; $\text{LiSCN} > \text{LiI} > \text{LiBr} > \text{LiCl}$; $\text{NaSCN} > \text{NaI}$. The salt concentration, solution temperature, and the preparation methods of chitin were also found to affect its dissolution behaviors, although details of the dissolution process and the chitin solubility have not been revealed.

Clark and Smith reported the detailed dissolution process of chitin in LiSCN aqueous solution.^[42] Typically, the saturated LiSCN solution at 60 °C was chosen as chitin solvent, which can readily dissolve chitin upon heating to 95 °C. LiI can also dissolve chitin, but the dissolution rate is lower than that of LiSCN. Vincendon and co-authors found that chitin could be dissolved in fresh saturated lithium thiocyanate (LiSCN) solutions to obtain a highly viscous chitin solution (3 wt%).^[50] Chemical shifts in the ^{13}C -NMR spectra of the chitin/LiSCN aqueous solutions are listed in Table 2. The disappearance of amide carbon signals is probably owing to the strong ionic interaction between the Li^+ ion and the *N*-acetyl group.^[50] The LiSCN aqueous solution is a non-derivative solvent of chitin.

Despite the aforementioned studies, the literature on chitin/inorganic salt aqueous solutions is very limited, and the detailed dissolution mechanism has not been reported.

Alkali Aqueous Solutions

Chitin viscose was prepared through the xanthation of alkali chitin in 1972 by applying a freezing procedure similar to that for cellulose viscose.^[51,52] In 1975, the dissolution of chitin in alkali aqueous solutions was reported by Sannan, Kurita, and Iwakura.^[53] Chitin could be dissolved in NaOH aqueous solutions, by first immersion in a concentrated NaOH solution and then mixing with ice. According to Vårum and co-authors, a typical dissolution process was as follows. Powdered chitin was suspended in 40 wt% NaOH and kept at 4 °C for 72 h, and then the mixture was diluted to 10 wt% NaOH using crushed ice.^[54] They found that 2.77 mol/L NaOH was a good solvent for chitin, and the second virial coefficients were in the range of 1×10^{-3} – 2×10^{-3} mL·mol/g². The established Mark-Houwink equation of chitin in 10 wt% NaOH is $[\eta] = 0.10M_w^{0.68}$ (mL/g), suggesting a random-coil chain conformation in the solution state.

The dissolution process can be divided into three steps: (1) formation of chitin/alkali complex in concentrated NaOH solution, (2) freezing, (3) diluting the NaOH to a low concentration with ice. The key in this multi-step method is to control the concentration of NaOH and the temperature in the dissolution process. Feng *et al.* studied the structural changes of chitin in 50 wt% NaOH aqueous solution after a

freeze-thaw process through X-ray diffractometry (Fig. 5).^[55] An increase in the crystalline interplanar spacing of α -chitin was detected after the alkali-freezing process, and the (020) crystalline plane exhibited the most prominent expansion.

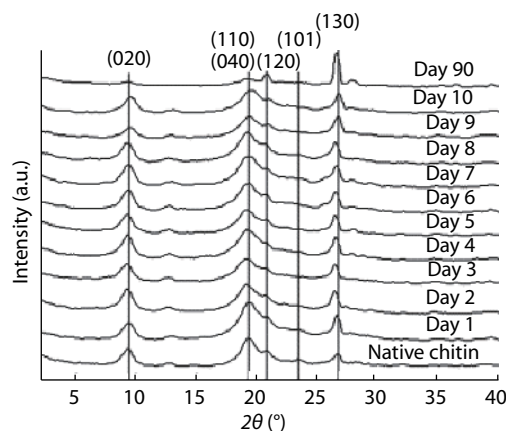


Fig. 5 X-ray diffraction profiles of chitin at different alkali-freezing treatment time (Reproduced with permission from Ref. [55]; Copyright (2004) Elsevier).

While developing solvents for cellulose, Zhang and co-authors found that cellulose can be rapidly dissolved in NaOH/urea and LiOH/urea aqueous solutions without using the freeze-thaw cycle.^[56–58] It was proposed that the fast dynamic self-assembly of small solvent molecules and cellulose at low temperature leads to the rapid dissolution of cellulose in NaOH/urea aqueous solutions.^[59] In 2007, Du and co-authors reported that chitin could be dissolved in NaOH/urea aqueous solutions after a freeze-thaw procedure.^[60] Using a 10 wt% NaOH/8 wt% urea solution as solvent, a maximum solubility of 91% was reached when dissolving 2 wt% chitin ($M_n = 1.88 \times 10^6$ g·mol^{−1}) at −20 °C. Cai and co-authors found that the maximum dissolution of chitin could be achieved using 11 wt% NaOH/4 wt% urea solution,^[61] whereas insufficient NaOH or urea would lead to incomplete dissolution of chitin, and excessive NaOH or urea would lead to quick gelation.

Besides NaOH, LiOH and KOH have also been tested for dissolving chitin (Fig. 6).^[31,62,63] The chemical shifts of chitin carbon are listed in Table 2. Cai and co-authors found that KOH/urea aqueous solution dissolved chitin under low temperature after one freeze-thaw cycle,^[36,64] whereas two and three repeated freeze-thaw cycles were needed to completely dissolve α -chitin in NaOH/urea and LiOH/urea aqueous solutions, respectively. This suggests the following order for the dissolution powers alkali hydroxide/urea aqueous solvents for α -chitin: aqueous KOH/urea > NaOH/urea > LiOH/urea. Moreover, the alkali/urea aqueous solutions were shown to be non-derivatizing solvents for α -chitin.

Notably, Cai and co-authors found that the precooling KOH/urea aqueous solution with a composition of 3.5 mol·L^{−1} KOH/0.67 mol·L^{−1} urea can dissolve α - and β -chitin in minutes without freezing (Fig. 7),^[31,62,63,65] and this can dramatically reduce the dissolution time and energy consumption. The high efficiency and accessibility of the KOH/urea aqueous solution

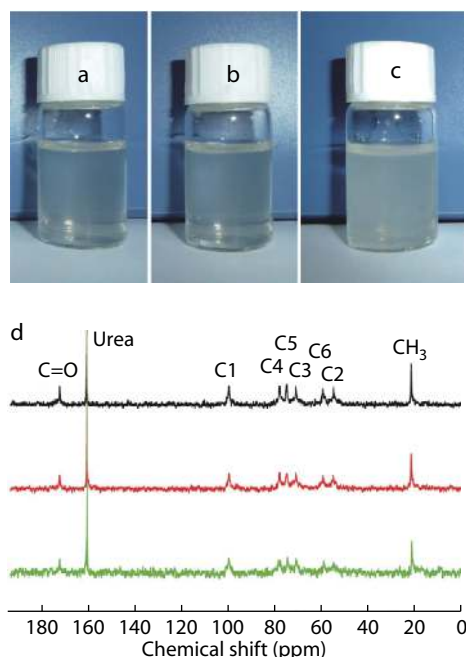


Fig. 6 Photographs of α -chitin in the solutions of (a) KOH/urea, (b) NaOH/urea, and (c) LiOH/urea after 1, 2, and 3 freeze-thaw cycles, respectively. (d) ^{13}C -NMR spectra of α -chitin in KOH/urea/D₂O (black), NaOH/urea/D₂O (red), and LiOH/urea/D₂O (green) solutions (Reproduced with permission from Ref. [64]; Copyright (2016) Springer Nature).

are promising for the large-scale utilization of chitin. In addition, the KOH aqueous system can dissolve chitosan, the main derivative of chitin, suggesting its potential as a universal solvent system for chitin and chitosan.^[66]

Zhang, Xu, and co-authors evaluated the properties of chitin NaOH/urea aqueous solutions. After storage at 5 °C, there were slight loss in viscosity (~5% after 25 h) and slight loss in the degree of acetylation (~5% after 45 h).^[67] The solution also displayed wormlike chain structures with a structure-sensitive parameter (ρ) > 2.0 and a persistent length of ~30 nm (Figs. 8a–8d). Compared with the random-coil structure in the NaOH aqueous solutions reported by Vårnum *et al.*,^[54] it was suggested that chitin chains in NaOH solutions become more rigid after introducing urea to the alkali solvent system.

The dissolution mechanism of chitin in NaOH/urea aqueous solution has also attracted considerable attention. Du and co-authors proposed that when chitin was immersed in aqueous NaOH/urea solution at room temperature, water molecules could penetrate into chitin chains with the help of NaOH. The volume expansion of the solvent molecules at the freezing point broke the inter- and intra-molecular hydrogen bonds between the chitin chains and promoted the dissolution of chitin (Fig. 8e).^[60] When the treatment temperature is lower than –30 °C, the freezing and expansion processes become shorter as the temperature decreases, leading to weaker expanding effects and lower solubility. Here, urea prevents the aggregation of chitin chains and increases their stability in the aqueous solution.

Huang found that the rapid dissolution of chitin in KOH/

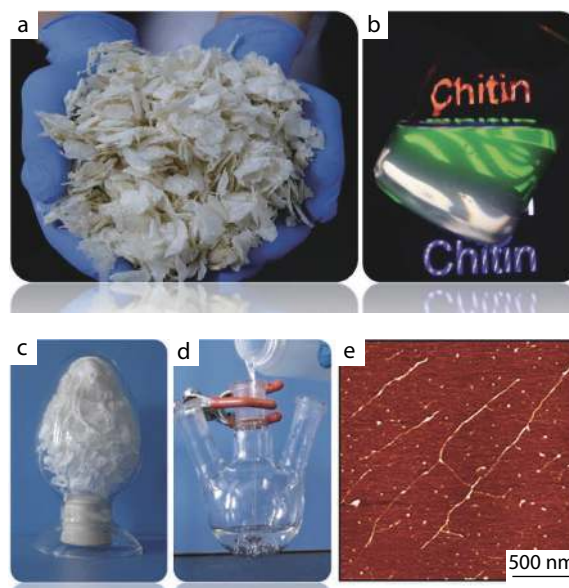


Fig. 7 Photographs of (a) the shrimp shells and (b) the α -chitin solution (Reproduced with permission from Ref. [31]; Copyright (2017) WILEY-VCH). Photographs of (c) the purified β -chitin and (d) the β -chitin solution; (e) AFM images of isolated chitin chains from an aqueous KOH/urea solution on mica (Reproduced with permission from Ref. [65]; Copyright (2018) WILEY-VCH).

urea aqueous solution relies on the disruption of intra- and intermolecular hydrogen bonding by (1) the strong ion-dipole interaction between hydrated K⁺ ions and carbonyl oxygen, (2) the hydrogen bonding interaction between hydroxyl groups and hydrated OH[–] ions, and (3) the weakened hydrophobic interaction between chitin chains through preferential adsorption of urea to the pyran rings of chitin.^[63]

Zhang, Lu, Liu, and co-authors proposed that the strong interaction between cations (Na⁺ and K⁺) and carbonyl oxygen of chitin resulted in the stronger dissolution power of NaOH and KOH as compared to LiOH (Fig. 9).^[68] Zhang, Xu, and co-authors proposed that the dissolution of chitin at low temperatures is a typical enthalpy-driven process.^[67] Chitin is dissolved in NaOH/urea aqueous solutions by forming a hydrogen-bonded chitin/NaOH complex, which is surrounded by the urea hydrates. This sheath-like structure leads to good solubilization of chitin (Fig. 8f). Wang, Feng, and co-authors interpreted the role of urea in a different way.^[69] They found that the NaOH/D₂O mixture was almost completely frozen at –40 °C. After adding urea, the crystallization of NaOH hydrates was depressed, resulting in a low-temperature residual liquid phase. They proposed that the dissolution of chitin occurred in this low-temperature residual liquid phase, and that the residual liquid phase can be enhanced in turn by the appearance of chitin.

It is worth noting that most studies on the dissolution mechanism of chitin were performed in solutions by exploring the interaction between chitin (or its model compounds) and solvents. However, changes in the aggregated structure of chitin in the whole dissolution process have not been tracked so far. Therefore, current understanding on the dissolution mechanism of chitin in solvents remains incomplete.

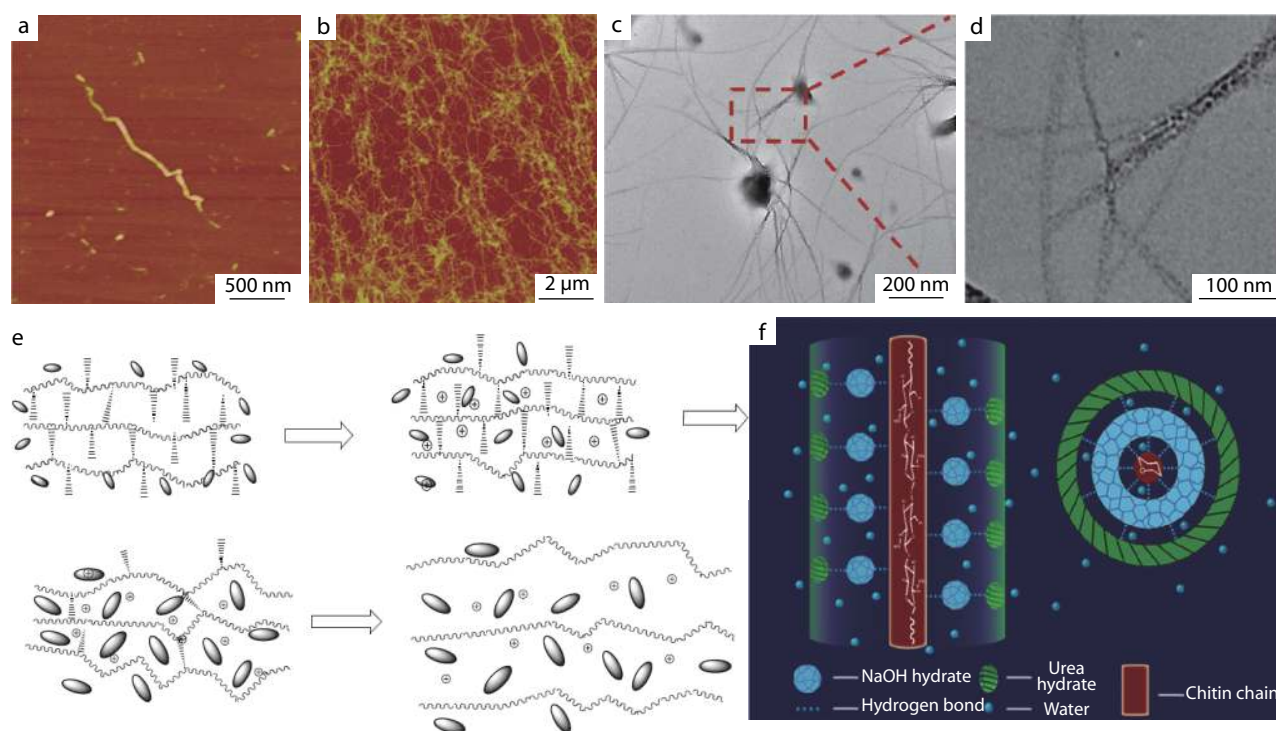


Fig. 8 AFM images of dilute chitin solutions at (a) 0.001 mg/mL and (b) 0.1 mg/mL; (c, d) TEM images of chitin solutions at 1 mg/mL in NaOH/urea aqueous solutions (Reproduced with permission from Ref. [67]; Copyright (2015) American Chemical Society). (e) Schematics showing the dissolution process of chitin in NaOH/urea aqueous solution via the freeze-thaw method (Reproduced with permission from Ref. [60]; Copyright (2007) Elsevier). (f) A model description of chitin complex chain in NaOH/urea aqueous solution (Reproduced with permission from Ref. [67]; Copyright (2015) American Chemical Society).

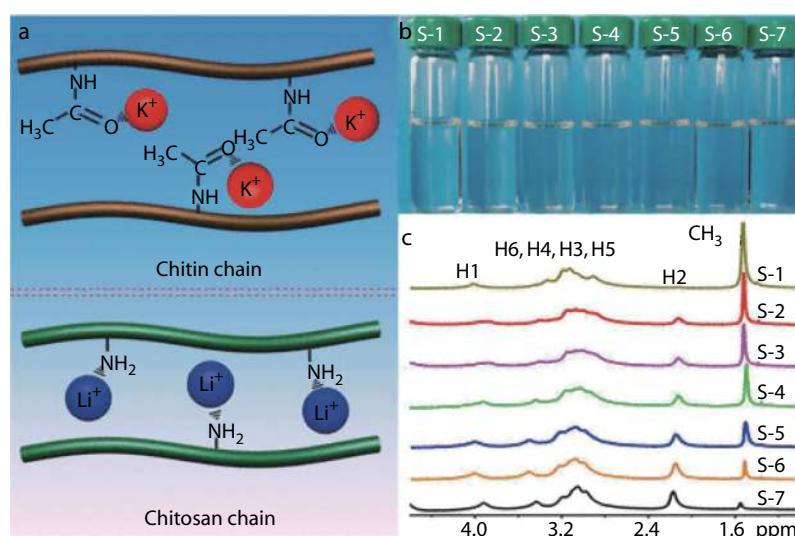


Fig. 9 (a) Schematic model to qualitatively describe the interactions between alkali and chitin/chitosan; (b) Photographs of transparent chitin/chitosan aqueous solutions; (c) ¹H-NMR spectra of chitin/chitosan aqueous solutions (Reproduced with permission from Ref. [68]; Copyright (2017) American Chemical Society).

NON-AQUEOUS SOLVENTS

LiCl/DMAc

The utilization of acidic solvents has been hampered due to the quick degradation of polymer chains in them. Searching for non-degradative solvents, Austin reported in 1977 for the first time that dimethylacetamide (DMAc) and *N*-methylpyrrolidone

(NMP) mixed with LiCl can be used as a chitin solvent.^[70] Compared with the corrosive acid solvents, the LiCl/DMAc solvent provides a stable chitin solution platform for material preparation and solution characterization at ambient temperature.^[71] Poirier and Charlet established the Mark-Houwink equation ($[\eta] = KM_n^a$) for chitin in LiCl/DMAc solution with the constants of $a = 0.95$ and $K = 7.6 \times 10^{-5}$.^[71] The exponent a is

larger than 0.8, indicating relatively stiff chitin chains in the solution state. Zhong *et al.* mentioned that chitin nanofibers with a typical height of 3 and 10 nm can be prepared from 0.01 wt% and 0.1 wt% chitin solutions in DMAc/LiCl, respectively (Figs. 10a and 10b).^[27]

LiCl/DMAc has proven to be a powerful complex solvent system for several insoluble polymers, such as polyamide, chitin, and cellulose. The interaction between the solvent components has attracted much attention. Germain and Vincendon found that LiCl is weakly dissociated in DMAc, suggesting ion pair formation in this solvent system.^[72] The weakly dissociated LiCl interacts strongly with DMAc, leading to the formation of LiCl-DMAc complex.

The molecular interaction between solvent and chitin has been characterized by nuclear magnetic resonance (NMR) techniques. Since the high viscosity of chitin LiCl/DMAc solution inevitably weakens the NMR signal, *N*-acetyl-D-glucosamine (GlcNAc, monomer) and methyl- β -D-chitobioside (dimer) were chosen as model compounds in place of chitin (Fig. 10c). By plotting the change of hydroxyl proton chemical shift with the LiCl concentration in DMAc, Vincendon found that there was a strong interaction between the GlcNAc labile protons and LiCl molecules at the molar ratio of 1:1.^[73] Therefore, a “sandwich” structure was proposed for the interaction between GlcNAc and LiCl-DMAc (Fig. 10d). In the solution of dimer in LiCl/DMAc, the hydroxyl proton of O3H is distinguished from other labile protons by exhibiting a lower chemical shift that is also insensitive to temperature, suggesting that the O3H...O5' hydrogen bonding is preserved in the solution state.^[73] For the chitin/LiCl-DMAc solution, the influence of temperature on the shift of O3H labile protons shows a smaller $\Delta\delta/\Delta T$ (1.8×10^{-3} ppm/°C) than that of the dimer (1.25×10^{-3} ppm/°C), suggesting stronger hydrogen bonding. Therefore, chitin dissolution was attributed to the strong in-

teraction of LiCl molecule with the hydroxyl and acetamido groups in chitin, which destroys the $\text{NH}\cdots\text{O}=\text{C}$ and $\text{O6H}\cdots\text{O}=\text{C}$ intermolecular hydrogen bonds, allowing chitin to swell and then to dissolve in the solvent. However, the intramolecular $\text{O3H}\cdots\text{O5'}$ hydrogen bond is unaffected by this dissolution mechanism and preserved in the solution state, leading to a stiff chain conformation.^[73]

Studying the viscosity behavior of chitin in LiCl/DMAc solutions, Fonseca and co-authors proposed that lithium-carbonyl complexation plays a very important role in the solubilization of chitin, similar to that for cellulose solutions in LiCl/DMAc (Fig. 10e).^[74] The formation of these charged regions makes chitin behave like a polyelectrolyte. The high charge density of chitin in LiCl/DMAc solution results in a rigid, extended macromolecular chain conformation.

Notably, the LiCl/DMAc solvent system is sensitive to water, which would impair its dissolving ability.^[75] Introduction of water into the organic medium could cause increased ionization, which is detrimental to the dissolution potential of the complex solvent.^[72] Besides, the toxicity of Li^+ and DMAc limit their use in biological applications.^[76,77]

Saturated $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ /Methanol

In 1995, Tokura and co-authors reported that saturated $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ methanol solution (calcium solvent) was a good chitin solvent.^[78,79] In a typical dissolution process, α -chitin powder was suspended in the calcium solvent and refluxed for several hours with stirring to achieve dissolution.^[80] The water content and calcium concentration are the two main factors affecting the dissolution of chitin. The optimum molar ratio between CaCl_2 and water is 1:2, the same as the composition of $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ salt. The maximum chitin solubility was reached in the saturated $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ methanol solution. Chitin is also partially soluble in saturated $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ ethanol solution and $\text{Ca}(\text{SCN})_2\cdot 4\text{H}_2\text{O}/\text{MeOH}$ (200 g/100 mL MeOH). It was proposed

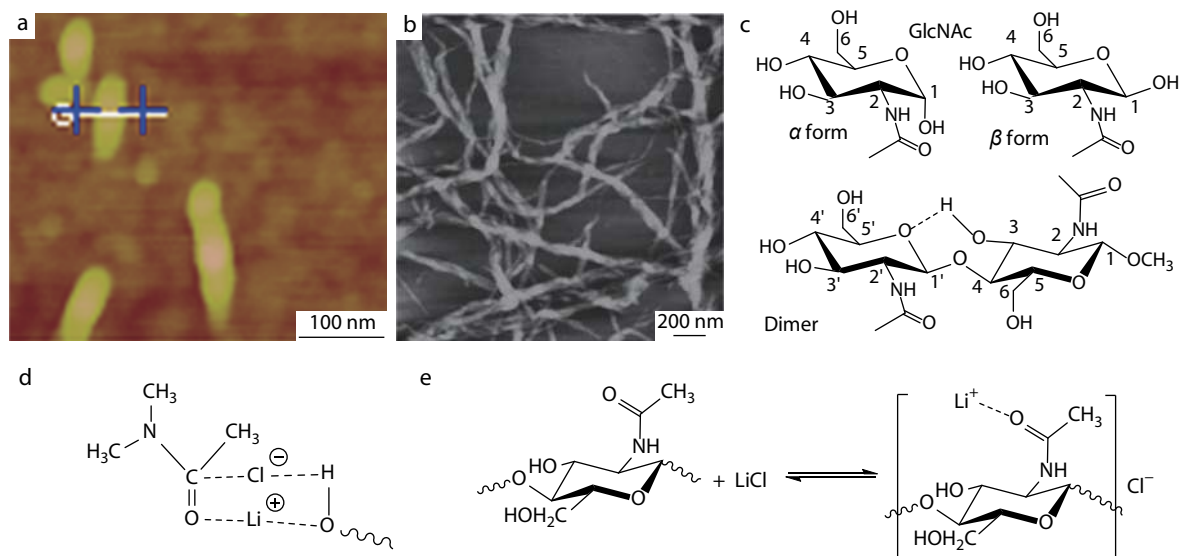


Fig. 10 AFM images of regenerated chitin nanofiber from (a) 0.01 wt% chitin and (b) 0.1 wt% chitin LiCl/DMAc solutions (Reproduced with permission from Ref. [27]; Copyright (2010) Royal Society of Chemistry). (c) Chemical structures of the α -form and β -form of GlcNAc, and the dimer model compound of chitin, (d) schematics of the proposed GlcNAc-LiCl-DMAc complex (Reproduced with permission from Ref. [73]; Copyright (1985) Hüthig & Wepf Verlag, Basel). (e) Schematics of the proposed chitin LiCl-DMAc complex (Reproduced with permission from Ref. [74]; Copyright (2011) Elsevier).

that chelate formation between the calcium ions and the acetamide groups is the main driving force for the dissolution of chitin by destroying the rigid crystalline structure. The supporting experimental findings are: (1) a better solubility was observed for the reacylated chitin than for native chitin, (2) similar solubility was also found for Nylon 6,6 and polyamide consisting of amide groups, and (3) chitin with a lower degree of acetylation showed decreased solubility.^[79,80]

The detailed mechanism for chitin dissolution in calcium solvent remains unknown.^[81] Considering the structural similarities between Nylon 6,6 and chitin (both having amide groups and abundant intermolecular $\text{C}=\text{O}\cdots\text{HN}$ hydrogen bonding), the dissolution mechanism of Nylon 6,6 in $\text{CaCl}_2/\text{methanol}$ solvent may be used for reference.

Sun proposed that in the CaCl_2 methanol solvent, the calcium cation and methanol form a $\text{CaCl}_2\text{-CH}_3\text{OH}$ complex.^[82] This complex is adsorbed on Nylon 6,6 through the hydrogen bonding of $\text{OH}\cdots\text{O}=\text{C}$. The calcium ion forms a stronger complex with the carbonyl group than with the hydroxyl group, leading to the formation of CaCl_2 -Nylon 6,6 complex and the release of methanol (Fig. 11).^[82] In the dissolution process, methanol plays the role similar to a catalyst. The complexation of a Lewis acid with a Lewis base can disturb the intermolecular hydrogen bonding in polymers and promote their dissolution.

Kamide and co-authors reported that at low CaCl_2 concentrations (below 4.7 wt%), the dissociated Ca^{2+} and Cl^- ions strongly interact with methanol. At high CaCl_2 concentrations (40 wt%), these ions could form a $[\text{Ca}(\text{CH}_3\text{OH})_4]^{2+}(\text{Cl}^-)_2$ complex (Fig. 12).^[83] It was found that the carbonyl oxygen of Nylon 6,6 interacts with the hydroxyl protons of methanol in this complex, while the amide NH protons interact with Cl^- or $\text{CH}_3\text{OH}\cdots\text{Cl}^-$, suggesting strong hydrogen bonding interactions between the amide groups and the solvent complex.^[83]

Despite the ability to dissolve chitin, calcium solvent is not a suitable platform for homogeneous chemical modification, because a high calcium concentration would affect the functional groups of chitin.^[80] Besides, the high viscosity, flammability, and volatility of the calcium solvent make it unfavourable in industrial production.

Ionic Liquids

Ionic liquids (ILs) are salts of organic cations and organic or inorganic anions that are liquid at low temperatures ($< 100^\circ\text{C}$).^[84] Only certain ILs can dissolve chitin, and the representative ones

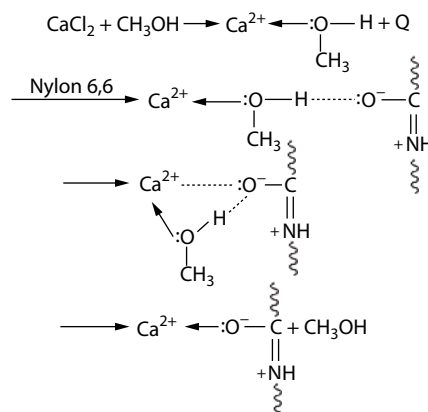


Fig. 11 Schematics of the formation of CaCl_2 -Nylon 6,6 complex (Reproduced with permission from Ref. [82]; Copyright (1994) Chinese Chemical Society, Institute of Chemistry (CAS) and Springer-Verlag GmbH Germany, a part of Springer Nature).

are listed in Table 3. Rogers and co-authors reported the successful dissolution of cellulose in the IL 1-butyl-3-methylimidazolium chloride ($[\text{Bmim}]\text{Cl}$) in 2002.^[85] At the same time, it was also shown that $[\text{Bmim}]\text{Cl}$ ^[86,87] and 1-butyl-3-methylimidazolium acetate ($[\text{Bmim}]\text{OAc}$)^[88] can be used for solubilization and derivatization of chitin, although the details were not given in the literature.^[89] Later, Zhang and co-authors reported in 2006 that chitin could be dissolved in $[\text{Bmim}]\text{Cl}$ at 110°C under an inert atmosphere.^[90] Wu and co-authors found that $[\text{Bmim}]\text{OAc}$ has better dissolving potential than $[\text{Bmim}]\text{Cl}$, and attributed it to the stronger hydrogen-bond accepting properties of acetate ions, which disrupts the hydrogen bonding networks in the chitin chains by depriving the proton of the amino ($-\text{NH}$) or hydroxyl groups.^[91] Kadokawa and co-authors reported that $[\text{Bmim}]\text{Br}$ and 1-methyl-3-propylimidazolium bromide showed no ability to dissolve chitin, whereas 1-allyl-3-methylimidazolium bromide ($[\text{Amim}]\text{Br}$) possessed great dissolving ability.^[92] Their report suggested that the cations of ILs also have a significant effect on chitin dissolution.

Rogers and co-authors reported that 1-ethyl-3-methylimidazolium acetate ($[\text{Emim}]\text{OAc}$ or $[\text{C}_2\text{mim}]\text{OAc}$) can directly dissolve chitin with no need for deproteinization and demineralization.^[93] It can be used to extract chitin directly from crustacean shells while maintaining the high molecular weight of natural chitin that is beneficial to spinning fibers

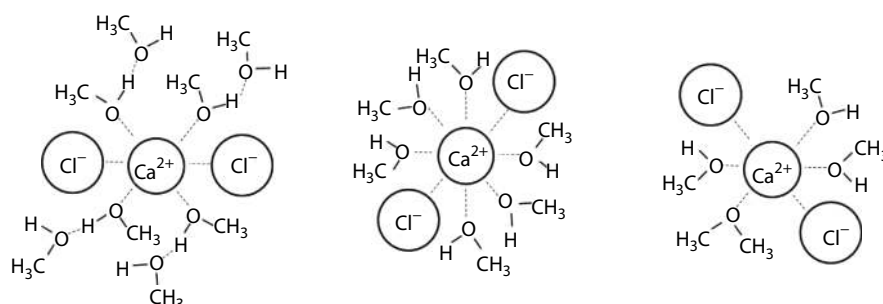


Fig. 12 Schematic representation of CaCl_2 -methanol complex in the solvent mixture at 40°C at $0.1 \leq W_{\text{Ca}}$ (mass fraction of CaCl_2 in calcium solvent) ≤ 0.15 (left), $0.15 < W_{\text{Ca}} \leq 0.175$ (middle), and $W_{\text{Ca}} = 0.4$ (right) (Reproduced with permission from Ref. [83]; Copyright (1995) Springer Nature).

Table 3 Representative ILs that can dissolve chitin.

Compound name	Chemical structure
[Bmim]Cl	
[Bmim]OAc or [C ₄ mim]OAc	
[Emim]OAc or [C ₂ mim]OAc	
[C ₄ C ₄ im]OAc	
[C ₁ mim]OAc	
[Amim]Br	
[Amim]OAc	

with high strength. In addition, microwave heating (3 s pulses at full power for 2 min, with vigorous stirring between pulses) can improve the dissolution efficiency significantly, reducing the time from hours in oven heating to 2 min of microwave heating. Besides, they found that a “statistical mixture” of different ILs can demonstrate a better dissolving power than any individual ILs.^[94] For example, in a “statistical mixture” of 1-butyl-3-methylimidazolium ([C₄mim][OAc]), 1,3-dibutylimidazolium ([C₄C₄im][OAc]), and 1,3-dimethylimidazolium acetate ([C₁mim][OAc]) with a molar ratio of 2:1:1, the chitin solubility is 1.6 times higher than that in neat [C₄mim][OAc] or [C₁mim][OAc].

Wang and co-authors reported that [Amim]OAc also shows prominent chitin dissolution ability, whereas [Amim]Cl and [Bmim]Cl have weak and no dissolution ability, respectively.^[95] Unlike the common dissolution temperatures when using other ILs (above 100 °C), a lower temperature of 45 °C was required for [Amim]Cl to dissolve chitin. They proposed that Cl[−] is a weaker hydrogen bond acceptor than OAc[−]. A lower temperature can strengthen its hydrogen bonding accepting ability, which would improve the dissolution ability.

Kamlet and Taft *et al.* used the solvatochromic comparison method to probe particular solvent properties, and established a set of parameters such as α , β , and π^* to describe the hydrogen-bond donor acidity, hydrogen-bond acceptor basicity, and polarity-polarizability effects, respectively.^[96–99] It was shown that the Kamlet-Taft parameters α and β of ILs mainly depend on the cations and anions, respectively.^[100] Ohno and co-authors found that the tris(2-hydroxyethyl) methylammonium (THEMA) type ILs with β values in the range of 0.09–0.41 were unable to dissolve chitin, while those with $\beta = 0.52$ –0.67 could partially dissolve it (0.1 wt% chitin for solubility test).^[101] After adding ethylenediamine (EDA), which increased the β values of the tested THEMA type ILs, complete dissolution was observed for only certain ILs ([THEMA]OAc and [THEMA]MeOSO₃), suggesting that the β value is an important but not the only factor governing the chitin dissolution. In addition, chitin is less soluble in ILs with higher α values, which show relatively high viscosity.

Kadokawa and co-authors used molecular dynamics (MD) simulation to evaluate the dissolution behavior of α -chitin

crystal in imidazolium-based ILs.^[102] The results show that the dissolution process in [Amim]Br can be described by a peeling model, namely “peeling” of chitin chains from the crystal surface *via* cleaving the hydrogen bonds of chitin (Fig. 13). Specifically, the Br[−] ions disrupt the hydrogen bonding network in chitin crystal through forming amide NH...Br...HO hydrogen bonding to induce twisting and peeling in the chitin chains. Meanwhile, [Amim]⁺ prevents the peeled chitin chains from going back to the crystalline phase by entering the gaps between the chains. In contrast, in ILs that are poor solvents for chitin, the peeled chains occasionally return to the crystalline phase since the cations could not occupy the gaps between chitin chains quickly enough. They found that Cl[−] prefers to interact with hydroxyl groups rather than amide groups, whereas Br[−] and OAc[−] are the opposite. Another important factor is the self-diffusion coefficient, which shows an inverse correlation with the viscosity. It turned out that most good solvents have a high self-diffusion coefficient, suggesting the dissolution of chitin in ILs is determined by the synergy between kinetic and thermodynamic effects.^[102]

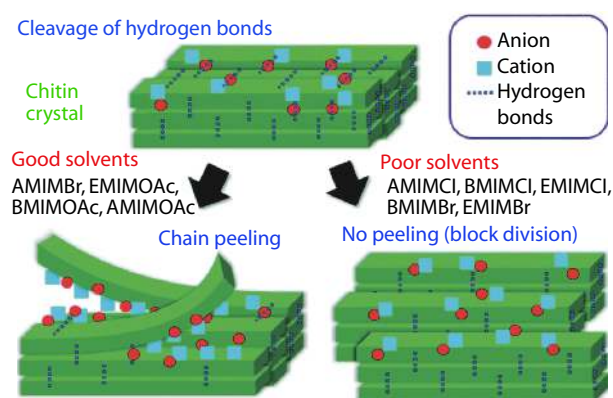


Fig. 13 Schematic models for the dissolution process of chitin crystal in imidazolium-based ILs (Reproduced with permission from Ref. [102]; Copyright (2018) Royal Society of Chemistry).

The toxicity and environmental impacts of ILs have generated some concern.^[103] Also, the hydrolysis and flammability of ILs need to be evaluated.^[104,105] It was found that the toxic effect of imidazolium ILs increases with the length of the side chain. The most promising ILs, namely [Emim]OAc with ethyl and methyl side chains, are relatively safe choices among current ILs for scale-up industrial utilization owing to their short side chains.^[89,106] The strong dissolving power and ability to extract chitin directly from shrimp shells make [Emim]OAc an excellent platform for chitin isolation and processing.

Deep Eutectic Solvents

Deep eutectic solvents (DESs) are mixed liquids containing two or more compounds, with a significantly lowered melting temperature than each of the individual components. A series of DESs can be prepared by mixing quaternary ammonium salts (hydrogen bond acceptors, HBAs) with hydrogen bonding donors (HBD) such as amides, amines, alcohols, and acids.^[107–109] The most investigated DES is choline chloride-urea (CCU), which is prepared by mixing choline chloride (Fig. 14a) and urea (Fig. 14b) in 1:2 molar ratio as reported by Abbott and

co-authors in 2003. The freezing point of CCU is 12 °C, considerably lower than those of choline chloride (302 °C) and urea (133 °C). In CCU, Cl^- is complexed with two urea molecules to form the $[\text{Cl}(\text{Urea})_2]^-$ complex anion (Fig. 14c).^[107,108,110] This complex anion is associated with the $[\text{Choline}]^+$ cation and migrates in the solution, showing a certain conductivity at room temperature similar to ILs.^[107] Hunt and co-authors reported that the hydrogen-bonded urea $[\text{Choline}]^+$ complex cation (Fig. 14d) is energetically competitive with $[\text{Cl}(\text{Urea})_2]^-$, suggesting a strong interaction between urea $[\text{Choline}]^+$ and urea $[\text{Cl}]^-$ in CCU.^[111]

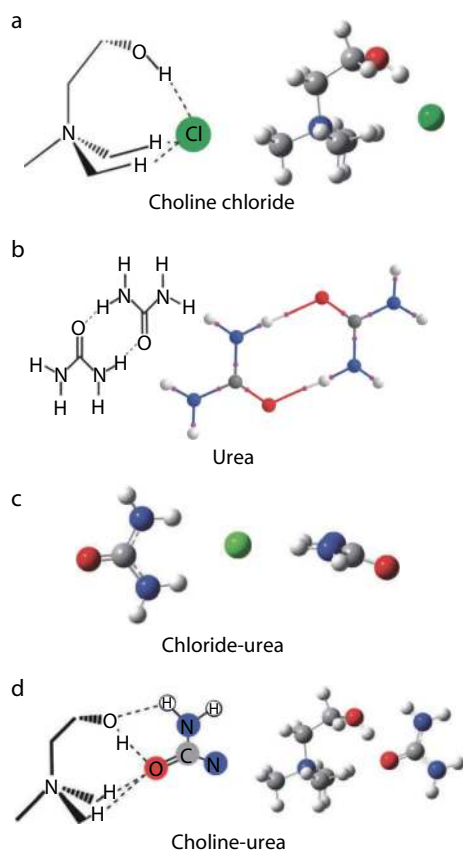


Fig. 14 (a) Chemical structures of choline chloride $[\text{Choline}]\text{Cl}$, (b) urea chain dimer, (c) $[\text{Cl}(\text{urea})_2]^-$ complex, and (d) urea $[\text{Choline}]^+$ (Reproduced with permission from Ref. [111]; Copyright (2016) Royal Society of Chemistry).

Prasad and co-authors reported that DESs such as CCU, choline bromide-urea, chlorocholine chloride-urea, betaine hydrochloride-urea, and choline chloride-thiourea (CCT) could be used to dissolve chitin.^[112,113] Typically, chitin was mixed with DES and heated under an inert atmosphere to realize dissolution. CCU and CCT are good solvents for dissolving chitin ($M_w = 5.22 \times 10^5$ g/mol) at 100 °C, with a maximum concentration of 6 wt% and 9 wt%, respectively. It was proposed that the stronger interaction between the amide groups with thiourea is responsible for the higher dissolving ability of CCT than CCU. The insolubility of chitosan in both CCT and CCU also confirms the indispensable role played by the acetamido groups of chitin. In addition, other DESs com-

prised of choline chloride-ethylene glycol and choline chloride-glycerol were found ineffective for dissolving both chitin and cellulose. They attributed this to the inability of these HBD molecules to break the hydrogen bonds in chitin.

Kadokawa and co-authors prepared DES by mixing imidazolium ILs with thiourea in order to improve the chitin dissolving ability.^[114] They found that most of the tested ILs, such as $[\text{Amim}]\text{Cl}$, $[\text{Emim}]\text{Cl}$, $[\text{Bmim}]\text{Br}$, and $[\text{Emim}]\text{Br}$, had enhanced chitin solubility after adding thiourea, whereas $[\text{Bmim}]\text{Cl}$ showed no improvement. It was suggested that both substituents on the imidazolium rings and the counter anions of the ILs could influence dissolution ability of the prepared DES.

The representative DES solvents of chitin are shown in Table 4. So far, their underlying dissolution mechanism has not been clarified. The hydrogen bond interaction and Lewis acid-base interaction between the DES components make this solvent system rather complicated compared to the ILs.

Table 4 Representative deep eutectic solvents for chitin.

Chemical structure	HBA	HBD	<i>M</i>	<i>S</i> (wt%)	Ref.
	Choline chloride	Urea	1:2	6.0	[112]
	Choline bromide	Urea	1:2	6.5	[112]
	Chlorocholine chloride	Urea	1:2	8.5	[112]
	Betaine hydrochloride	Urea	1:4	5.0	[112]
	Choline chloride	Thio-urea	1:2	9.0	[112]
	$[\text{Amim}]\text{Cl}$	Thio-urea	1:0.5	5.0	[114]
	$[\text{Bmim}]\text{Br}$	Thio-urea	1:0.5	5.0	[114]
	$[\text{Emim}]\text{Cl}$	Thio-urea	1:0.3	2.0	[114]
	$[\text{Emim}]\text{Br}$	Thio-urea	1:0.5	2.0	[114]

HBA denotes hydrogen bond acceptor. HBD denotes hydrogen bond donor. *M* denotes the molar ratio of HBA:HBD. *S* denotes the solubility of chitin.

HFIP

Hexafluoroisopropanol (HFIP) is a fluorine-containing compound with a low boiling point, a high polarity, and strong dissolving ability for various polymers.^[115] Because of the strong negative inductive effect of fluorine, the acidity ($\text{pK}_a = 9.3$) of the hydroxyl hydrogen is strengthened significantly. Thus, HFIP is also a strong hydrogen bonding donor. Compared with other protic organic solvents of chitin such as formic acid,^[50] dichloroacetic acid, trichloroacetic acid, and methanesulfonic acid,^[116,117] HFIP is less degradative and corrosive.

Buffington and Stevens reported the far-ultraviolet circular dichroism spectra of chitin/HFIP solution and chitin gels.^[118] In the chitin HFIP solutions, the amide groups are solvated by HFIP. Removal of the HFIP-amide interaction would increase the solute-solute interaction, forming hydrogen bonding between amide groups and leading to the gelation of chitin. It was found that only the *trans* amide conformation would

permit the amide groups to participate in two types of hydrogen bonds as both donors and acceptors, crosslinking the chitin chains and forming chitin gels.

Park and co-authors reported that α -chitin can be dissolved in HFIP for electrospinning.^[119] In a typical dissolution process, chitin powder was first depolymerized to $M_w = 9.1 \times 10^4$ and then dissolved in HFIP for 3 days. The solubility of chitin is related to the molecular weight, and its maximum concentration is approximately 0.65 wt% for $M_w \approx 9.1 \times 10^5$ and 6 wt% for $M_w = 9.1 \times 10^4$. Rolandi and co-authors reported that β -chitin dissolved in HFIP can self-assemble to form chitin nanofibers through evaporation of the solvent.^[27] Considering this fast self-assembly process, they hypothesized that HFIP had dissolved chitin through hydrogen bond disruption without itself forming any bonds with chitin, leading to the quick evaporation of solvent and the formation of chitin nanofibers through intermolecular hydrogen bonding.

HFIP has an advantage over other solvent systems in the regeneration process, in that no regeneration bath is needed when fabricating chitin nanopapers and films.^[27,119] The low boiling point (58.6 °C) and thermal stability of HFIP facilitate its removal from the chitin solution.^[115] The detailed dissolution mechanism of chitin in HFIP has not been reported so far, however.

CONCLUSIONS AND OUTLOOK

In this review article, we discussed past research endeavors on chitin solvents and their possible dissolution mechanisms. We can find common ground and gain insight from these solvent systems. The proposed dissolution mechanisms of chitin have focused on disrupting hydrogen bonding interactions among the amide groups and hydroxyl groups of chitin through strong hydrogen bonding and Lewis acid-base interactions between the chitin chains and solvents. Besides, additives such as urea and thiourea can help improve the dissolving power of some specific solvent systems including alkali aqueous solvents, ILs, and DESs. Results from other polymers such as polyamide and cellulose have also contributed to the development of chitin solvents. Differences in the chemical structure and the aggregated structure of these macromolecules may lead to completely different rules of dissolution, which will bring us new perspectives on the dissolution mechanism of polymers.

The mentioned solvent systems allow facile and efficient chitin processing and preparation of chitin-based functional materials. Notably, the alkali solvents are a much safer choice for chitin-based materials including fibers, films, hydrogels, aerogels, microspheres, and chitin derivatives.^[14,31,36,39,61,65] The alkali can play the role of a catalyst when crosslinking chitin chains and fabricating chitin derivatives in etherification, deacetylation, and alkylation reactions.^[26,36,65] The appealing bioactivity, biocompatibility, biodegradability, and mechanical property would make chitin-based materials promising in food additives, wound dressings, packaging materials, electrochemical energy materials, and flexible electronics. We believe that new techniques and theories developed in the future regarding chitin processing would deepen our comprehensive understanding on the structure and properties of biomacromolecules in general.

ABBREVIATIONS

Cations of ILs

[Amim]	1-Allyl-3-methylimidazolium
[Bmim]	1-Butyl-3-methylimidazolium
[Emim]	1-Ethyl-3-methylimidazolium
[C ₁ mim]	1,3-Dimethylimidazolium
[C ₂ mim]	1-Ethyl-3-methylimidazolium
[C ₄ mim]	1-Butyl-3-methylimidazolium
[C ₄ C ₄ im]	1,3-Dibutylimidazolium

Anions of ILs

Br	Bromide
Cl	Chloride
OAc	Acetate

ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (No. 21875170). The authors thank to the facility support of the Special Fund for the Development of Strategic Emerging Industries of Shenzhen City of China (Nos. JCYJ20180507184711069 and JCYJ20170818112409808), Fundamental Research Funds for the Central Universities (No. 2042019kf0276), and Wuhan Morning Light Plan of Youth Science and Technology (No. 2017050304010312).

REFERENCES

- Kumar, M. N. V. R. A review of chitin and chitosan applications. *React. Funct. Polym.* **2000**, *46*, 1–27.
- Bartlett, D. H.; Azam, F. Chitin, cholera, and competence. *Science* **2005**, *310*, 1775.
- Nawawi, W. M. F. B. W.; Jones, M.; Murphy, R. J.; Lee, K. Y.; Kontturi, E.; Bismarck, A. Nanomaterials derived from fungal sources—Is it the new type? *Biomacromolecules* **2020**, *21*, 30–55.
- Food and Agriculture Organization of the United Nations. *The state of world fisheries and aquaculture (FAO, 2018)*. **2018**, <https://apo.org.au/node/181941>.
- Crini, G. Historical landmarks in the discovery of chitin. In *Sustainable agriculture reviews 35: chitin and chitosan: history, fundamentals and innovations*, Crini, G.; Lichtfouse, E. Eds. Springer International Publishing, **2019**, DOI: 10.1007/978-3-030-16538-3_1.
- Rudall, K. M. The chitin/protein complexes of insect cuticles. In *Advances in insect physiology*. Beament, J. W. L.; Treherne, J. E.; Wigglesworth, V. B. Eds. Academic Press, **1963**, p.1.
- Blackwell, J.; Gardner, K. H.; Kolpak, F. J.; Minke, R.; Claffey, W. B. Refinement of cellulose and chitin structures. In *Fiber diffraction methods*, American Chemical Society, **1980**, p.141.
- Sikorski, P.; Hori, R.; Wada, M. Revisit of α -chitin crystal structure using high resolution X-ray diffraction data. *Biomacromolecules* **2009**, *10*, 1100–1105.
- Nishiyama, Y.; Noishiki, Y.; Wada, M. X-ray structure of anhydrous β -chitin at 1 Å resolution. *Macromolecules* **2011**, *44*, 950–957.
- Sawada, D.; Nishiyama, Y.; Langan, P.; Forsyth, V. T.; Kimura, S.; Wada, M. Direct determination of the hydrogen bonding arrangement in anhydrous β -chitin by neutron fiber diffraction. *Biomacromolecules* **2012**, *13*, 288–291.
- Krajewska, B. Application of chitin- and chitosan-based materials for enzyme immobilizations: a review. *Enzyme Microb. Technol.* **2004**, *35*, 126–139.
- Jayakumar, R.; Menon, D.; Manzoor, K.; Nair, S. V.; Tamura, H.

- Biomedical applications of chitin and chitosan based nanomaterials—a short review. *Carbohydr. Polym.* **2010**, *82*, 227–232.
- 13 Kadokawa, J. I. Ionic liquid as useful media for dissolution, derivatization, and nanomaterial processing of chitin. *Green Sustain. Chem.* **2013**, *3*, 19–25.
 - 14 Duan, B.; Huang, Y.; Lu, A.; Zhang, L. Recent advances in chitin based materials constructed via physical methods. *Prog. Polym. Sci.* **2018**, *82*, 1–33.
 - 15 Zavgorodnya, O.; Shamshina, J. L.; Berton, P.; Rogers, R. D. Translational research from academia to industry: following the pathway of George Washington Carver. In *Ionic liquids: current state and future directions*, American Chemical Society, **2017**, p.1250.
 - 16 Wu, S.; Duan, B.; Zeng, X.; Lu, A.; Xu, X.; Wang, Y.; Ye, Q.; Zhang, L. Construction of blood compatible lysine-immobilized chitin/carbon nanotube microspheres and potential applications for blood purified therapy. *J. Mater. Chem. B* **2017**, *5*, 2952–2963.
 - 17 Shen, X.; Shamshina, J. L.; Berton, P.; Gurau, G.; Rogers, R. D. Hydrogels based on cellulose and chitin: fabrication, properties, and applications. *Green Chem.* **2016**, *18*, 53–75.
 - 18 Shamshina, J. L.; Berton, P.; Rogers, R. D. Advances in functional chitin materials: a review. *ACS Sustain. Chem. Eng.* **2019**, *7*, 6444–6457.
 - 19 Zhang, L.; Wang, J.; Yang, M.; Ke, N.; Zhang, B.; Wang, H.; Zheng, Q.; Xie, H. Dissolution, materialization and derivatization of chitin and chitosan in ionic liquids. *Sci. Sin. Chim.* **2019**, *49*, 1059–1072.
 - 20 Wei, P.; Cai, J.; Zhang, L. High-strength and tough crystalline polysaccharide-based materials. *Chin. J. Chem.* **2020**, DOI: 10.1002/cjoc.202000036.
 - 21 Marchessault, R. H.; Morehead, F. F.; Walter, N. M. Liquid crystal systems from fibrillar polysaccharides. *Nature* **1959**, *184*, 632–633.
 - 22 Fan, Y.; Saito, T.; Isogai, A. Chitin nanocrystals prepared by TEMPO-mediated oxidation of α -chitin. *Biomacromolecules* **2008**, *9*, 192–198.
 - 23 Fan, Y.; Saito, T.; Isogai, A. TEMPO-mediated oxidation of β -chitin to prepare individual nanofibrils. *Carbohydr. Polym.* **2009**, *77*, 832–838.
 - 24 Fan, Y.; Saito, T.; Isogai, A. Individual chitin nano-whiskers prepared from partially deacetylated α -chitin by fibril surface cationization. *Carbohydr. Polym.* **2010**, *79*, 1046–1051.
 - 25 You, J.; Zhu, L.; Wang, Z.; Zong, L.; Li, M.; Wu, X.; Li, C. Liquid exfoliated chitin nanofibrils for re-dispersibility and hybridization of two-dimensional nanomaterials. *Chem. Eng. J.* **2018**, *344*, 498–505.
 - 26 Kurita, K. Controlled functionalization of the polysaccharide chitin. *Prog. Polym. Sci.* **2001**, *26*, 1921–1971.
 - 27 Zhong, C.; Cooper, A.; Kapetanovic, A.; Fang, Z.; Zhang, M.; Rolandi, M. A facile bottom-up route to self-assembled biogenic chitin nanofibers. *Soft Matter* **2010**, *6*, 5298–5301.
 - 28 You, J.; Li, M.; Ding, B.; Wu, X.; Li, C. Crab chitin-based 2D soft nanomaterials for fully biobased electric devices. *Adv. Mater.* **2017**, *29*, 1606895.
 - 29 Duan, B.; Chang, C.; Ding, B.; Cai, J.; Xu, M.; Feng, S.; Ren, J.; Shi, X.; Du, Y.; Zhang, L. High strength films with gas-barrier fabricated from chitin solution dissolved at low temperature. *J. Mater. Chem. A* **2013**, *1*, 1867–1874.
 - 30 King, C.; Shamshina, J. L.; Gurau, G.; Berton, P.; Khan, N. F. A. F.; Rogers, R. D. A platform for more sustainable chitin films from an ionic liquid process. *Green Chem.* **2017**, *19*, 117–126.
 - 31 Huang, J. C.; Zhong, Y.; Zhang, L. N.; Cai, J. Extremely strong and transparent chitin films: a high-efficiency, energy-saving, and "green" route using an aqueous KOH/urea solution. *Adv. Funct. Mater.* **2017**, *27*, 1701100.
 - 32 Zhu, K.; Shi, S.; Cao, Y.; Lu, A.; Hu, J.; Zhang, L. Robust chitin films with good biocompatibility and breathable properties. *Carbohydr. Polym.* **2019**, *212*, 361–367.
 - 33 Huang, Y.; Zhong, Z.; Duan, B.; Zhang, L.; Yang, Z.; Wang, Y.; Ye, Q. Novel fibers fabricated directly from chitin solution and their application as wound dressing. *J. Mater. Chem. B* **2014**, *2*, 3427–3432.
 - 34 Zhu, K.; Tu, H.; Yang, P.; Qiu, C.; Zhang, D.; Lu, A.; Luo, L.; Chen, F.; Liu, X.; Chen, L.; Fu, Q.; Zhang, L. Mechanically strong chitin fibers with nanofibril structure, biocompatibility, and biodegradability. *Chem. Mater.* **2019**, *31*, 2078–2087.
 - 35 Chang, C.; Chen, S.; Zhang, L. Novel hydrogels prepared via direct dissolution of chitin at low temperature: structure and biocompatibility. *J. Mater. Chem.* **2011**, *21*, 3865–3871.
 - 36 Xu, D. D.; Huang, J. C.; Zhao, D.; Ding, B. B.; Zhang, L. N.; Cai, J. High-flexibility, high-toughness double-cross-linked chitin hydrogels by sequential chemical and physical cross-linkings. *Adv. Mater.* **2016**, *28*, 5844–5849.
 - 37 Duan, B.; Zheng, X.; Xia, Z.; Fan, X.; Guo, L.; Liu, J.; Wang, Y.; Ye, Q.; Zhang, L. Highly biocompatible nanofibrous microspheres self-assembled from chitin in NaOH/urea aqueous solution as cell carriers. *Angew. Chem. Int. Ed.* **2015**, *54*, 5152–5156.
 - 38 Duan, B.; Gao, X.; Yao, X.; Fang, Y.; Huang, L.; Zhou, J.; Zhang, L. Unique elastic N-doped carbon nanofibrous microspheres with hierarchical porosity derived from renewable chitin for high rate supercapacitors. *Nano Energy* **2016**, *27*, 482–491.
 - 39 Duan, B.; Shou, K.; Su, X.; Niu, Y.; Zheng, G.; Huang, Y.; Yu, A.; Zhang, Y.; Xia, H.; Zhang, L. Hierarchical microspheres constructed from chitin nanofibers penetrated hydroxyapatite crystals for bone regeneration. *Biomacromolecules* **2017**, *18*, 2080–2089.
 - 40 Duan, B.; Gao, H.; He, M.; Zhang, L. Hydrophobic modification on surface of chitin sponges for highly effective separation of oil. *ACS Appl. Mater. Interfaces* **2014**, *6*, 19933–19942.
 - 41 Knecht, E.; Hibbert, E. Some observations relating to chitin. *J. Soc. Dyers Colour.* **1926**, *42*, 343–345.
 - 42 Clark, G. L.; Smith, A. F. X-ray diffraction studies of chitin, chitosan, and derivatives. *J. Phys. Chem.* **1936**, *40*, 863–879.
 - 43 Meyer, K. H.; Wehrli, H. Comparaison chimique de la chitine et de la cellulose. *Helv. Chim. Acta* **1937**, *20*, 353–362.
 - 44 Hackman, R. H. Studies on chitin V. The action of mineral acids on chitin. *Aust. J. Biol. Sci.* **1962**, *15*, 526–537.
 - 45 Nagasawa, K.; Tohira, Y.; Inoue, Y.; Tanoura, N. Reaction between carbohydrates and sulfuric acid: Part I. Depolymerization and sulfation of polysaccharides by sulfuric acid. *Carbohydr. Res.* **1971**, *18*, 95–102.
 - 46 Vincendon, M. Regenerated chitin from phosphoric acid solutions. *Carbohydr. Polym.* **1997**, *32*, 233–237.
 - 47 Wu, T.; Wang, G.; Gao, C.; Chen, Z.; Feng, L.; Wang, P.; Zeng, X.; Wu, Z. Phosphoric acid-based preparing of chitin nanofibers and nanospheres. *Cellulose* **2016**, *23*, 477–491.
 - 48 von Weimarn, P. P. Conversion of fibroin, chitin, casein, and similar substances into the ropy-plastic state and colloidal solution. *Ind. Eng. Chem.* **1927**, *19*, 109–110.
 - 49 von Weimarn, P. P. Zur dispersoidchemie von cellulose. *Kolloidzeitschrift* **1912**, *11*, 41–47.
 - 50 Gagnaire, D.; Saintgermain, J.; Vincendon, M. NMR studies of chitin and chitin derivatives. *Macromol. Chem. Phys.* **1982**, *183*, 593–601.
 - 51 Musatova, G. N.; Mogilevskii, E. M.; Ginzberg, M. A.; Arkhangelskii, D. N. The dissolution temperature of cellulose xanthate. *Fibre Chem.* **1972**, *2*, 451–453.
 - 52 Noguchi, J.; Wada, O.; Seo, H.; Tokura, S.; Nishi, N. Chitin and

- chitosan-cellulose fibres. *Kobunshi Kagaku* **1973**, 30, 320–326.
- 53 Sannan, T.; Kurita, K.; Iwakura, Y. Studies on chitin, 1. Solubility change by alkaline treatment and film casting. *Makromol. Chem.* **1975**, 176, 1191–1195.
 - 54 Einbu, A.; Naess, S. N.; Elgsaeter, A.; Vårum, K. M. Solution properties of chitin in alkali. *Biomacromolecules* **2004**, 5, 2048–2054.
 - 55 Feng, F.; Liu, Y.; Hu, K. Influence of alkali-freezing treatment on the solid state structure of chitin. *Carbohydr. Res.* **2004**, 339, 2321–2324.
 - 56 Cai, J.; Zhang, L. Rapid dissolution of cellulose in LiOH/Urea and NaOH/Urea aqueous solutions. *Macromol. Biosci.* **2005**, 5, 539–548.
 - 57 Cai, J.; Zhang, L. Unique gelation behavior of cellulose in NaOH/Urea aqueous solution. *Biomacromolecules* **2006**, 7, 183–189.
 - 58 Cai, J.; Zhang, L.; Zhou, J.; Qi, H.; Chen, H.; Kondo, T.; Chen, X.; Chu, B. Multifilament fibers based on dissolution of cellulose in NaOH/urea aqueous solution: structure and properties. *Adv. Mater.* **2007**, 19, 821–825.
 - 59 Cai, J.; Zhang, L.; Liu, S. L.; Liu, Y. T.; Xu, X. J.; Chen, X. M.; Chu, B.; Guo, X. L.; Xu, J.; Cheng, H.; Han, C. C.; Kuga, S. Dynamic self-assembly induced rapid dissolution of cellulose at low temperatures. *Macromolecules* **2008**, 41, 9345–9351.
 - 60 Hu, X.; Du, Y.; Tang, Y.; Wang, Q.; Feng, T.; Yang, J.; Kennedy, J. F. Solubility and property of chitin in NaOH/urea aqueous solution. *Carbohydr. Polym.* **2007**, 70, 451–458.
 - 61 Ding, B.; Cai, J.; Huang, J.; Zhang, L.; Chen, Y.; Shi, X.; Du, Y.; Kuga, S. Facile preparation of robust and biocompatible chitin aerogels. *J. Mater. Chem.* **2012**, 22, 5801–5809.
 - 62 Cai, J.; Huang, J. C.; Zhang, L. N. **2013**, ZL 201310034088.4.
 - 63 Huang, J. *Rapid dissolution of chitin in potassium hydroxide/urea aqueous solution under low temperature, and preparation and characterization of novel materials*. Doctoral thesis, Wuhan University, Hubei, China, **2017**.
 - 64 Ding, B.; Zhao, D.; Song, J.; Gao, H.; Xu, D.; Xu, M.; Cao, X.; Zhang, L.; Cai, J. Light weight, mechanically strong and biocompatible α -chitin aerogels from different aqueous alkali hydroxide/urea solutions. *Sci. China Chem.* **2016**, 59, 1405–1414.
 - 65 Xu, H.; Fang, Z.; Tian, W.; Wang, Y.; Ye, Q.; Zhang, L.; Cai, J. Green fabrication of amphiphilic quaternized β -chitin derivatives with excellent biocompatibility and antibacterial activities for wound healing. *Adv. Mater.* **2018**, 30, 1801100.
 - 66 Cai, J.; Zhang, L. N. Method for continuously preparing chitin/chitosan solutions with different deacetylation degrees. **2017**, CN201711023349A.
 - 67 Fang, Y.; Duan, B.; Lu, A.; Liu, M.; Liu, H.; Xu, X.; Zhang, L. Intermolecular interaction and the extended wormlike chain conformation of chitin in NaOH/urea aqueous solution. *Biomacromolecules* **2015**, 16, 1410–1417.
 - 68 Fang, Y.; Zhang, R.; Duan, B.; Liu, M.; Lu, A.; Zhang, L. Recyclable universal solvents for chitin to chitosan with various degrees of acetylation and construction of robust hydrogels. *ACS Sustain. Chem. Eng.* **2017**, 5, 2725–2733.
 - 69 Ru, G.; Luo, H.; Liang, X.; Wang, L.; Liu, C.; Feng, J. Quantitative NMR investigation on the low-temperature dissolution mechanism of chitin in NaOH/urea aqueous solution. *Cellulose* **2015**, 22, 2221–2229.
 - 70 Austin, P. R. Chitin solution. **1977**, US4059457A.
 - 71 Poirier, M.; Charlet, G. Chitin fractionation and characterization in *N,N*-dimethylacetamide/lithium chloride solvent system. *Carbohydr. Polym.* **2002**, 50, 363–370.
 - 72 Germain, J. S.; Vincendon, M. ^1H , ^{13}C and ^7Li nuclear magnetic resonance study of the lithium chloride-*N,N*-dimethylacetamide system. *Org. Magn. Reson.* **1983**, 21, 371–375.
 - 73 Vincendon, M. ^1H NMR study of the chitin dissolution mechanism. *Makromol. Chem.* **1985**, 186, 1787–1795.
 - 74 de Vasconcelos, C. L.; Bezerril, P. M.; Pereira, M. R.; Ginani, M. F.; Fonseca, J. L. C. Viscosity-temperature behavior of chitin solutions using lithium chloride/DMA as solvent. *Carbohydr. Res.* **2011**, 346, 614–618.
 - 75 Austin, P. R.; Brine, C. J.; Castle, J. E.; Zikakis, J. P. Chitin: new facets of research. *Science* **1981**, 212, 749.
 - 76 Okuda, H.; Takeuchi, T.; Senoh, H.; Arito, H.; Matsushima, T. Developmental toxicity induced by inhalation exposure of pregnant rats to *N,N*-dimethylacetamide. *J. Occup. Health* **2006**, 48, 154.
 - 77 Gitlin, M. Lithium side effects and toxicity: prevalence and management strategies. *Int. J. Bipolar Disord.* **2016**, 4, 27.
 - 78 Tokura, S.; Nishi, N.; Takahashi, K.; Shirai, A.; Uraki, Y. Novel drug delivery system by chitin derivative. *Macromol. Symp.* **1995**, 99, 201–208.
 - 79 Tokura, S.; Nishimura, S. I.; Sakairi, N.; Nishi, N. Biological activities of biodegradable polysaccharide. *Macromol. Symp.* **1996**, 101, 389–396.
 - 80 Tamura, H.; Nagahama, H.; Tokura, S. Preparation of chitin hydrogel under mild conditions. *Cellulose* **2006**, 13, 357–364.
 - 81 Nagahama, H.; Higuchi, T.; Jayakumar, R.; Furuike, T.; Tamura, H. XRD studies of β -chitin from squid pen with calcium solvent. *Int. J. Biol. Macromol.* **2008**, 42, 309–313.
 - 82 Sun, B. Study on the mechanism of Nylon 6,6 dissolving process using $\text{CaCl}_2/\text{MeOH}$ as the solvent. *Chinese J. Polym. Sci.* **1994**, 12, 57–65.
 - 83 Hattori, M.; Saito, M.; Okajima, K.; Kamide, K. Molecular characterization of nylon 6,6 and its dissolved state in mixture of calcium chloride and methanol. *Polym. J.* **1995**, 27, 631–644.
 - 84 Wasserscheid, P.; Keim, W. Ionic liquids—new “solutions” for transition metal catalysis. *Angew. Chem. Int. Ed.* **2000**, 39, 3772–3789.
 - 85 Swatloski, R. P.; Spear, S. K.; Holbrey, J. D.; Rogers, R. D. Dissolution of cellose with ionic liquids. *J. Am. Chem. Soc.* **2002**, 124, 4974–4975.
 - 86 Reichert, W. M.; Swatloski, R. P.; Rogers, R. D. In *The 222nd ACS National Meeting*, Chicago, IL, **2001**.
 - 87 Reichert, W. M.; Swatloski, R. P.; Rogers, R. D. In *The 221st ACS National Meeting*, San Diego, CA, **2001**.
 - 88 Spear, S. K.; Swatloski, R. P.; Rogers, R. D. In *The 221st ACS National Meeting*, San Diego, CA, **2001**.
 - 89 Shamshina, J. L. Chitin in ionic liquids: historical insights into the polymer's dissolution and isolation a review. *Green Chem.* **2019**, 21, 3974–3993.
 - 90 Xie, H.; Zhang, S.; Li, S. Chitin and chitosan dissolved in ionic liquids as reversible sorbents of CO_2 . *Green Chem.* **2006**, 8, 630–633.
 - 91 Wu, Y.; Sasaki, T.; Irie, S.; Sakurai, K. A novel biomass-ionic liquid platform for the utilization of native chitin. *Polymer* **2008**, 49, 2321–2327.
 - 92 Prasad, K.; Murakami, M.; Kaneko, Y.; Takada, A.; Nakamura, Y.; Kadokawa, J. Weak gel of chitin with ionic liquid, 1-allyl-3-methylimidazolium bromide. *Int. J. Biol. Macromol.* **2009**, 45, 221–225.
 - 93 Qin, Y.; Lu, X.; Sun, N.; Rogers, R. D. Dissolution or extraction of crustacean shells using ionic liquids to obtain high molecular weight purified chitin and direct production of chitin films and fibers. *Green Chem.* **2010**, 12, 968–971.
 - 94 Rogers, R. D. **2019**, Application Number US2019/0040209A1.
 - 95 Wang, W. T.; Zhu, J.; Wang, X. L.; Huang, Y.; Wang, Y. Z. Dissolution behavior of chitin in ionic liquids. *J. Maromol. Sci. B* **2010**, 49, 528–541.
 - 96 Taft, R. W.; Kamlet, M. J. The solvatochromic comparison

- method. 2. The α -scale of solvent hydrogen-bond donor (HBD) acidities. *J. Am. Chem. Soc.* **1976**, 98, 2886–2894.
- 97 Kamlet, M. J.; Taft, R. W. The solvatochromic comparison method. I. The β -scale of solvent hydrogen-bond acceptor (HBA) basicities. *J. Am. Chem. Soc.* **1976**, 98, 377–383.
- 98 Yokoyama, T.; Taft, R. W.; Kamlet, M. J. The solvatochromic comparison method. 3. Hydrogen bonding by some 2-nitroaniline derivatives. *J. Am. Chem. Soc.* **1976**, 98, 3233–3237.
- 99 Kamlet, M. J.; Abboud, J. L.; Taft, R. W. The solvatochromic comparison method. 6. The π^* scale of solvent polarities. *J. Am. Chem. Soc.* **1977**, 99, 6027–6038.
- 100 Crowhurst, L.; Mawdsley, P. R.; Perez-Arlandis, J. M.; Salter, P. A.; Welton, T. Solvent–solute interactions in ionic liquids. *Phys. Chem. Chem. Phys.* **2003**, 5, 2790–2794.
- 101 Shimo, M.; Abe, M.; Ohno, H. Functional comparison of polar ionic liquids and onium hydroxides for chitin dissolution and deacetylation to chitosan. *ACS Sustain. Chem. Eng.* **2016**, 4, 3722–3727.
- 102 Uto, T.; Idenoue, S.; Yamamoto, K.; Kadokawa, J. I. Understanding dissolution process of chitin crystal in ionic liquids: theoretical study. *Phys. Chem. Chem. Phys.* **2018**, 20, 20669–20677.
- 103 Petkovic, M.; Seddon, K. R.; Rebelo, L. P. N.; Silva, Pereira C. Ionic liquids: a pathway to environmental acceptability. *Chem. Soc. Rev.* **2011**, 40, 1383–1403.
- 104 Swatloski, R. P.; Holbrey, J. D.; Rogers, R. D. Ionic liquids are not always green: hydrolysis of 1-butyl-3-methylimidazolium hexafluorophosphate. *Green Chem.* **2003**, 5, 361–363.
- 105 Smiglak, M.; Reichert, W. M.; Holbrey, J. D.; Wilkes, J. S.; Sun, L.; Thrasher, J. S.; Kirichenko, K.; Singh, S.; Katritzky, A. R.; Rogers, R. D. Combustible ionic liquids by design: is laboratory safety another ionic liquid myth? *Chem. Commun.* **2006**, 2554–2556.
- 106 Ostadjoo, S.; Berton, P.; Shamshina, J. L.; Rogers, R. D. Scaling-up ionic liquid-based technologies: how much do we care about their toxicity? Prima facie information on 1-ethyl-3-methylimidazolium acetate *Toxicol. Sci.* **2017**, 161, 249–265.
- 107 Abbott, A. P.; Capper, G.; Davies, D. L.; Rasheed, R. K.; Tambyrajah, V. Novel solvent properties of choline chloride/urea mixtures. *Chem. Commun.* **2003**, 70–71.
- 108 Abbott, A. P.; Boothby, D.; Capper, G.; Davies, D. L.; Rasheed, R. K. Deep eutectic solvents formed between choline chloride and carboxylic acids: versatile alternatives to ionic liquids. *J. Am. Chem. Soc.* **2004**, 126, 9142–9147.
- 109 Francisco, M.; van, den Bruinhorst A.; Kroon, M. C. New natural and renewable low transition temperature mixtures (LTTMs): screening as solvents for lignocellulosic biomass processing. *Green Chem.* **2012**, 14, 2153–2157.
- 110 Silva, L. P.; Araújo, C. F.; Abranches, D. O.; Melle-Franco, M.; Martins, M. A. R.; Nolasco, M. M.; Ribeiro-Claro, P. J. A.; Pinho, S. P.; Coutinho, J. A. P. What a difference a methyl group makes – probing choline-urea molecular interactions through urea structure modification. *Phys. Chem. Chem. Phys.* **2019**, 21, 18278–18289.
- 111 Ashworth, C. R.; Matthews, R. P.; Welton, T.; Hunt, P. A. Doubly ionic hydrogen bond interactions within the choline chloride-urea deep eutectic solvent. *Phys. Chem. Chem. Phys.* **2016**, 18, 18145–18160.
- 112 Sharma, M.; Mukesh, C.; Mondal, D.; Prasad, K. Dissolution of α -chitin in deep eutectic solvents. *RSC Adv.* **2013**, 3, 18149–18155.
- 113 Mukesh, C.; Mondal, D.; Sharma, M.; Prasad, K. Choline chloride-thiourea, a deep eutectic solvent for the production of chitin nanofibers. *Carbohydr. Polym.* **2014**, 103, 466–471.
- 114 Idenoue, S.; Yamamoto, K.; Kadokawa, J. I. Dissolution of chitin in deep eutectic solvents composed of imidazolium ionic liquids and thiourea. *ChemEngineering* **2019**, 3, 90.
- 115 Shuklov, I. A.; Dubrovina, N. V.; Boerner, A. Fluorinated alcohols as solvents, cosolvents and additives in homogeneous catalysis. *ChemInform* **2007**, 19, 2925–2943.
- 116 Tokura, S.; Nishi, N.; Noguchi, J. Studies on chitin. III. Preparation of chitin fibers. *Polym. J.* **1979**, 11, 781–786.
- 117 Austin, P. R. Chitin solutions and purification of chitin. In *Methods enzymol.* Academic Press, **1988**, 161.
- 118 Buffington, L. A.; Stevens, E. S. Far-ultraviolet circular dichroism of solutions, gels, and films of chitins. *J. Am. Chem. Soc.* **1979**, 101, 5159–5162.
- 119 Min, B. M.; Lee, S. W.; Lim, J. N.; You, Y.; Lee, T. S.; Kang, P. H.; Park, W. H. Chitin and chitosan nanofibers: electrospinning of chitin and deacetylation of chitin nanofibers. *Polymer* **2004**, 45, 7137–7142.