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REVIEWS

Research Progress and Development Trend of Textile Auxiliaries

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Abstract

Textiles hold a position of great importance in both the routines of everyday life and the intricacies of industrial production. Textile auxiliaries play a considerable role in the development of textile products, contributing to achievements such as enhanced color fastness, increased functionality, improved mechanical strength, shortened process, reduced energy consumption, and decreased greenhouse gas emissions. Here, an overview of the functionality and sustainability of dyeing and finishing auxiliaries is presented, highlighting their latest research achievements. Subsequently, the challenges encountered by textile auxiliary industries are exposed. Furthermore, an explicit identification of the development and international status of China's textile industries is undertaken. Finally, three innovative directions of textile auxiliaries are delineated based on policy orientation and market demand. Taking proactive measures to tackle these challenges and wholeheartedly embracing innovative solutions will be pivotal for staying abreast of evolving market trends and consumer demands, ultimately contributing to advancing the sustainable development and bolstering the competitiveness of the textile industry as a whole.

Keywords Textile auxiliaries · Sustainability · Functionality · Green chemical · Textile industry

1 Introduction

Textiles are fundamental components of production and daily life, encompassing diverse categories such as clothing (constituting 44% of usage in China), industrial textiles (approximately 29%), and household goods (around 27%) [1, 2]. A pivotal role is played by textile auxiliaries in elevating textile quality, imparting specialized functions to textiles, prolonging textile lifespan, and contributing to energy conservation and emission reduction efforts [3, 4]. Currently, the realm of textile auxiliaries encompasses roughly 100 distinct categories, comprising nearly 16,000 diverse variants. In 2021, the global consumption of textile chemicals amounted to 7.2 million tons, with a total valuation of $12.9 billion [5].

Textile auxiliaries are present at various stages of textile product development, as illustrated in Fig. 1. Textile raw materials primarily derive from plants (cotton, flax, wood, bamboo, etc.) [6–8], animals (silk and wool) [9, 10], and petroleum (polyester, nylon, acrylic, viscose, etc.) [11–13], corresponding to cellulose fibers (natural fibers), protein fibers (natural fibers), and synthetic fibers, respectively. Fibers are transformed into yarns through processes such as ring spinning, air spinning, melt spinning, dry spinning, and wet spinning [14–17]. At this stage, agents such as oils and antistatic agents begin to work. The conversion of yarns into esthetically appealing and functionally enriched fabrics involves steps such as sizing, weaving, pretreatment, dyeing, and finishing. Possible auxiliaries encompass sizing agents, desizing agents, scouring agents, bleaching agents, penetration enhancers, leveling agents, color fixation agents, thickening agents, binding agents, softeners, fluorescent brightening agents, wrinkle- and shrinkage-resistant finishing agents, hydrophobic and oleophobic finishing agents, stain-repellent finishing agents, flame-retardant finishing agents, antistatic finishing agents, antimicrobial and deodorizing finishing agents, ultraviolet (UV)-resistant finishing agents, and more. In addition, it is also hoped to achieve the recycling and effective degradation of waste textiles through auxiliaries.

Nonetheless, challenges arise from the prevalent instances of excessive and ill-considered utilization of textile auxiliaries. These challenges result in escalated textile expenses, heightened carbon emissions within the textile industry,

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increased energy consumption, and exacerbated complexities in wastewater treatment processes [18, 19]. Furthermore, the field of textile auxiliaries also demonstrates a noticeable phenomenon of developmental lag. This phenomenon pertains specifically to the absence of textile auxiliaries suited for novel fibers and aligned with environmentally sustainable practices.

In this review, the role and achievements of dyeing and finishing auxiliaries in the development of clothing textiles are first elucidated. Then, the main problems faced by the textile chemical industry at present are critically discussed. Moreover, the development and international status of China's textiles are revealed. Finally, three innovative directions of textile auxiliaries are anticipated according to the actual situation.

2 The Role and Achievements of Dyeing and Finishing Auxiliaries in the Development of Clothing Textiles

As shown in Fig. 2a, b, since 2000, articles and patents related to "Finishing auxiliaries," "Functional textile," "Textile auxiliaries," "Dyeing and printing auxiliaries," and "green textile auxiliaries" have shown an obvious rising trend. Significant advancements have been made in the production of high-quality textiles through extensive utilization of textile auxiliaries, which exhibit potential in catering to the diverse textile requirements of various fields and groups across different time periods. However, there are still several prospects for research to further enhance the existing textile auxiliaries and bridge the gap between their state-of-the-art status and practical implementation in the future production of eco-friendly and high-quality textiles. The practical application of advanced textile auxiliaries would necessitate a thorough evaluation of their functionality and sustainability. Figure 2c presents an overview of this chapter. In this

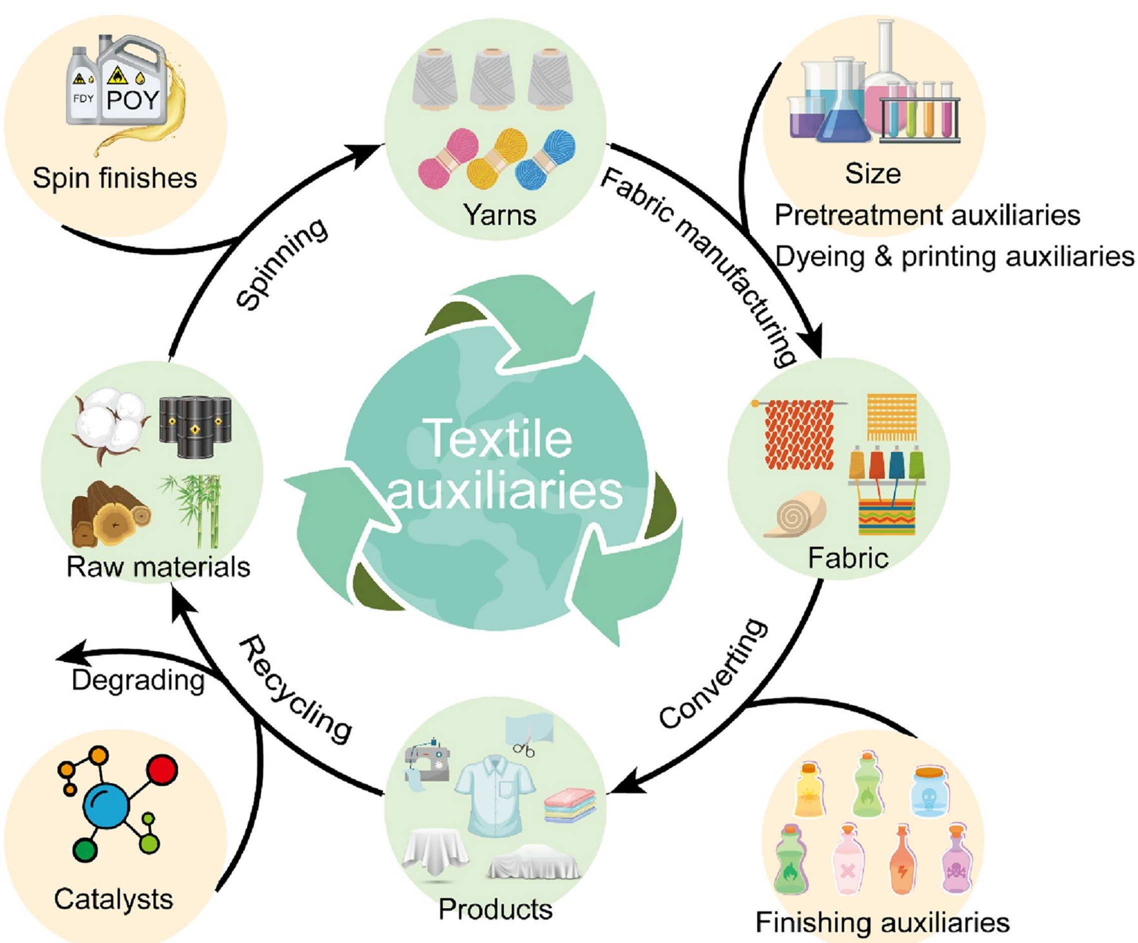


Fig. 1 Application of different textile auxiliaries in the development of textile products

chapter, a selection of representative types of textile auxiliaries is examined to elucidate their mechanisms of action and research status. Moreover, an in-depth exploration is conducted into the policy orientation and market demands closely associated with the textile industry, revealing the necessity for the development of green textile auxiliaries.

2.1 Functionality

2.1.1 Leveling Agents

Due to the physical and chemical heterogeneity of fibers, imperfect pretreatment technology, and varying adsorption properties of dyes, fabric dyeing often suffers from uneven phenomena such as color differences, spots, and stripes. Adding a leveling agent to the dye bath is one of the most effective and low-cost ways to achieve uniform dyeing. Leveling agents can be classified into three categories based on their mechanism of action: fiber affinity, dye affinity, and amphiphilic leveling agents. Fiber-affinity leveling agents compete with dyes for bonding sites on fibers, thereby limiting adsorption of both dye and fiber and delaying dyeing speed (Fig. 3a) [20]. As temperature increases, dyes gradually replace leveling agents until they occupy all available bonding sites on fibers to achieve uniformity.

Before dyes are absorbed by fibers, the dye-affinity leveling agents combine with dyes to form stable aggregates, which reduce the migration rate and diffusion speed of dyes and delay the dyeing time (Fig. 3b). At high temperatures, these stable aggregates come into contact with fibers, undergo decomposition, and then release dyes, which again combine with fibers to achieve the purpose of leveling. Unlike fiber-affinity leveling agents, dye-affinity leveling agents have the property of migration. To reduce the overdependence on petroleum-based surfactants, Chen et al. synthesized a series of biodegradable cardanol-based polyethoxylate oligomers (CPm) and revealed that CPm showed a higher hydroxyl value, better dispersing capability, and a higher migration percentage than those of tristyrylphenol ethoxylates (Fig. 3d) [21]. A series of vegetable oil-based non-ionic Gemini surfactant (GPNGS) was also used as a nylon 66 acid dye leveling agent[22].

Amphiphilic leveling agents not only occupy dye sites on fibers but also combine with dyes to form stable aggregates (Fig. 3c), which reduce the migration rate and diffusion speed of dyes and delay the dyeing time. The molecular structure of this type of leveling agent typically comprises both positively charged quaternary ammonium salts and negatively charged groups [23]. As depicted in Fig. 3e, leveling agents containing quaternary ammonium salts and sulfonic acid groups are particularly suitable for dyeing wool with acid dyes. Leveling agents with molecular weight between 200 and 300 (Fig. 3f) play an important role in acrylic fiber dyeing with cationic dyes. The leveling agent widely used in disperse dye dyeing is a combination of non-ionic surfactant and anionic surfactant. These two types of surfactants (Fig. 3g) complement each other and exhibit synergistic effects.

2.1.2 Dye-Fixing Agents

To maintain the stability of dyes, it is crucial to prevent external factors such as sweat, saliva, and ultraviolet rays from damaging them. This is achieved using appropriate additives to fix the fabric after dyeing. Low molecular cationic fixing agents are effective in forming ionic bonds with the anion groups of the dye, creating an insoluble color precipitation on the fabric that enhances its resistance to wet treatment. The reaction mechanism is illustrated in Fig. 4a. Cationic pyridine quaternary ammonium salts (Fig. 4b) are the most commonly used surfactants. The low molecular fixative of the non-surfactant (Fig. 4c) is widely utilized to improve the washing fastness of the dye and the soap washing fastness of the acid dye. Hossian et al. significantly improved the fixation rate (95.03%) and color strength (15.26) of the cacao husk extract-dyed cotton fabric by low molecular cationic dye fixation agent treatment [24]. Dimethyloctadecyl[3-(trimethoxysilyl)propyl] ammonium chloride was employed in the dyebath to fix acid dye to nylon fabric [25]. Bao et al. reported that green cationic silicon-based Gemini surfactants were beneficial in the absorption and fixation of the dye by sheepskin [26].

High molecular cationic color-fixing agent is the most widely used in the industry, accounting for more than 80%. According to the characteristics of molecular structure, it can be divided into formaldehyde condensation type, polyamine type, and cationic polymer type. Formaldehyde condensation fixing agent can form insoluble precipitate with dye anion. In addition, it can also generate a mesh film on the fiber surface, coating the dye on the fiber surface to prevent the dye from falling off, and further improve the wet processing fastness. Color-fixing agent Y is a famous product of this kind of color-fixing agent, and its structure is shown in Fig. 4d. Color-fixing agent M is to add metal salt on the basis of color-fixing agent Y to further improve the fastness to sunlight. However, fabrics treated with formalin condensation fixative have formaldehyde release problems, which pose a serious threat to environmental safety and consumer safety, so their application is currently limited. The other two formaldehyde-free fixing agents have subsequently become the first choice for research and application.

Polyamine dye-fixing agents are usually synthesized from dicyandiamide and polyvinyl polyamine, and the typical reaction formula is shown in Fig. 4e. This kind of fixing agent forms large molecules with dyes by means of its own

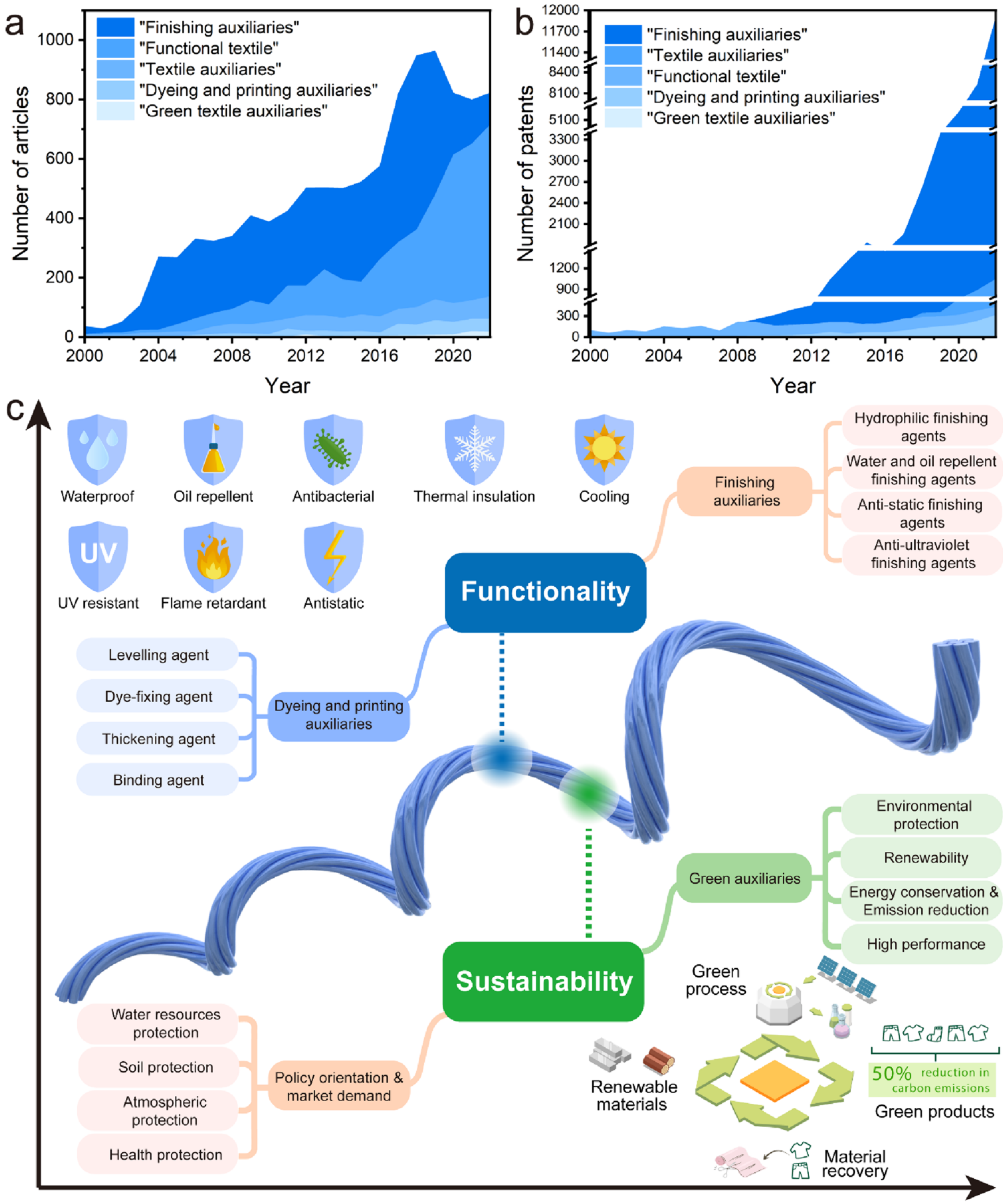


Fig. 2 **a** Number of articles searched with the keywords "Finishing auxiliaries," "Functional textile," "Textile auxiliaries," "Dyeing and printing auxiliaries," and "green textile auxiliaries" from 2000 to 2022, **b** number of patents searched with the keywords "Finishing auxiliaries," "Functional textile," "Textile auxiliaries," "Dyeing and printing auxiliaries," and "green textile auxiliaries" from 2000 to 2022, **c** schematic diagram of this chapter

network structure, so as to improve the color fastness of dyed fabrics. Jamadhar et al. pointed out that non-formaldehyde polyamine dye-fixing agent gave superior fastness properties as compared to formaldehyde-based fixing agent in reactive dyes [27]. Ugur used the Aysol Mordan T (polyamine) to impart cationic sites to the surfaces of the cotton fibers for fixing reactive or direct dyes [28]. Bairagi et al. assessed the antimicrobial properties of polyamine/epichlorohydrin polycondensate [29].

The molecular structure of the cationic polymer dye-fixing agent does not contain a quaternary ammonium salt structure and undergoes significant structural changes.

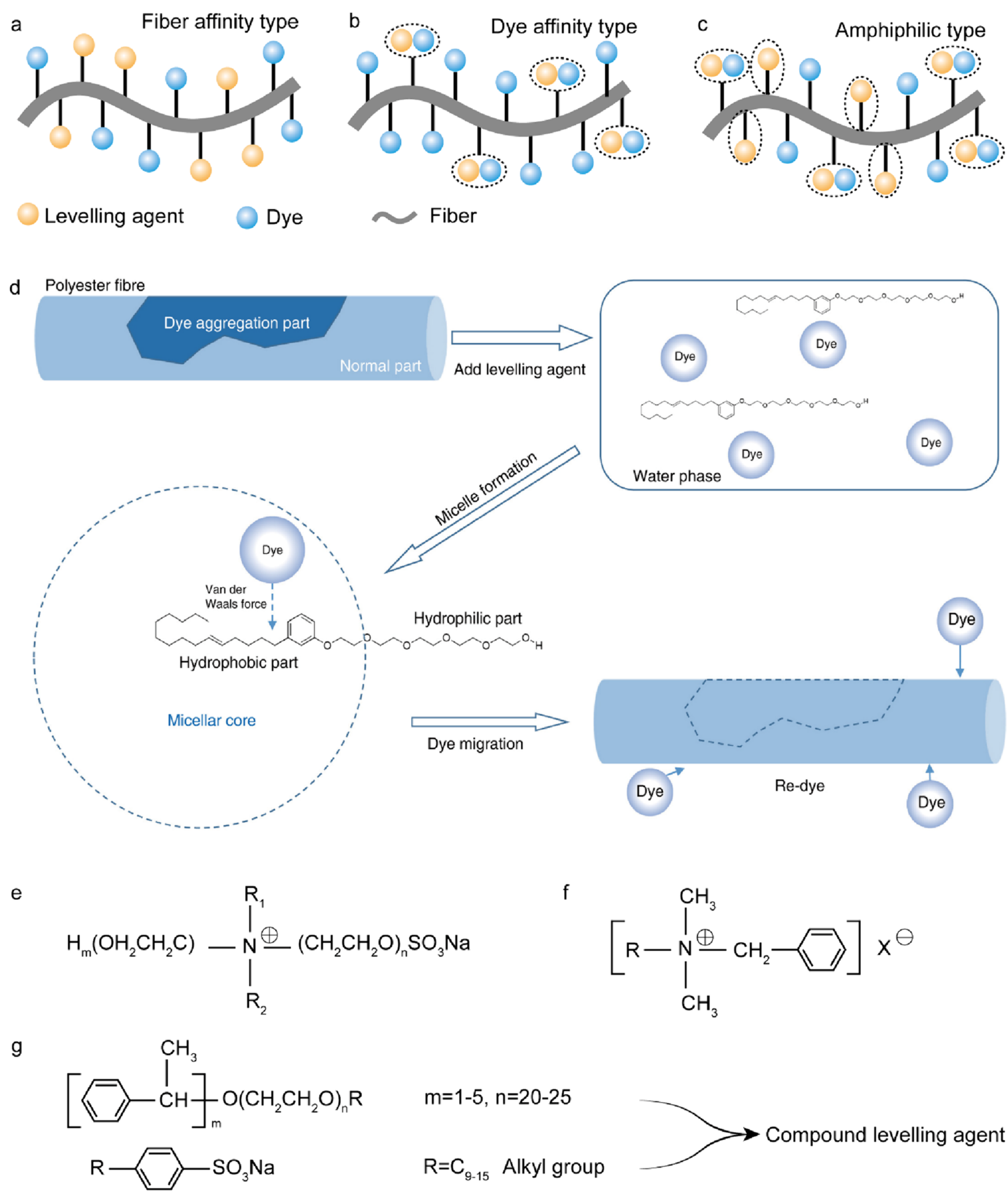


Fig. 3 **a–c** Mechanism diagram of three types of leveling agent, **d** schematic diagram of CPm as a leveling agent, reproduced with permission from Ref. [21], Copyright 2021, *Wiley*, **e** structure of leveling agents containing quaternary ammonium salts and sulfonic acid groups, **f** structure of leveling agents with molecular weight between 200 and 300, **g** structure of leveling agents containing non-ionic surfactant and anionic surfactant

Figure 4f lists several common molecular structural formulas. The dye-fixing agent containing hydroxyl can form hydrogen bonds with the amino group in the protein fiber and the hydroxyl group in the cellulose as well as dye molecules, thereby enhancing the color-fixing effect. Sundang et al. prepared a series of cationic polyurethane dispersions (CPU) as a fixing agent for denim fabric[30]. The color fastness to crocking and surface smoothness of the treated fabric have improved. Yu et al. studied the relationships between the molecular weight and the dye-fixing properties of poly(dimethyldiallylammonium chloride) (PDMDAAC, cationic polymer type) to access a new way for improving

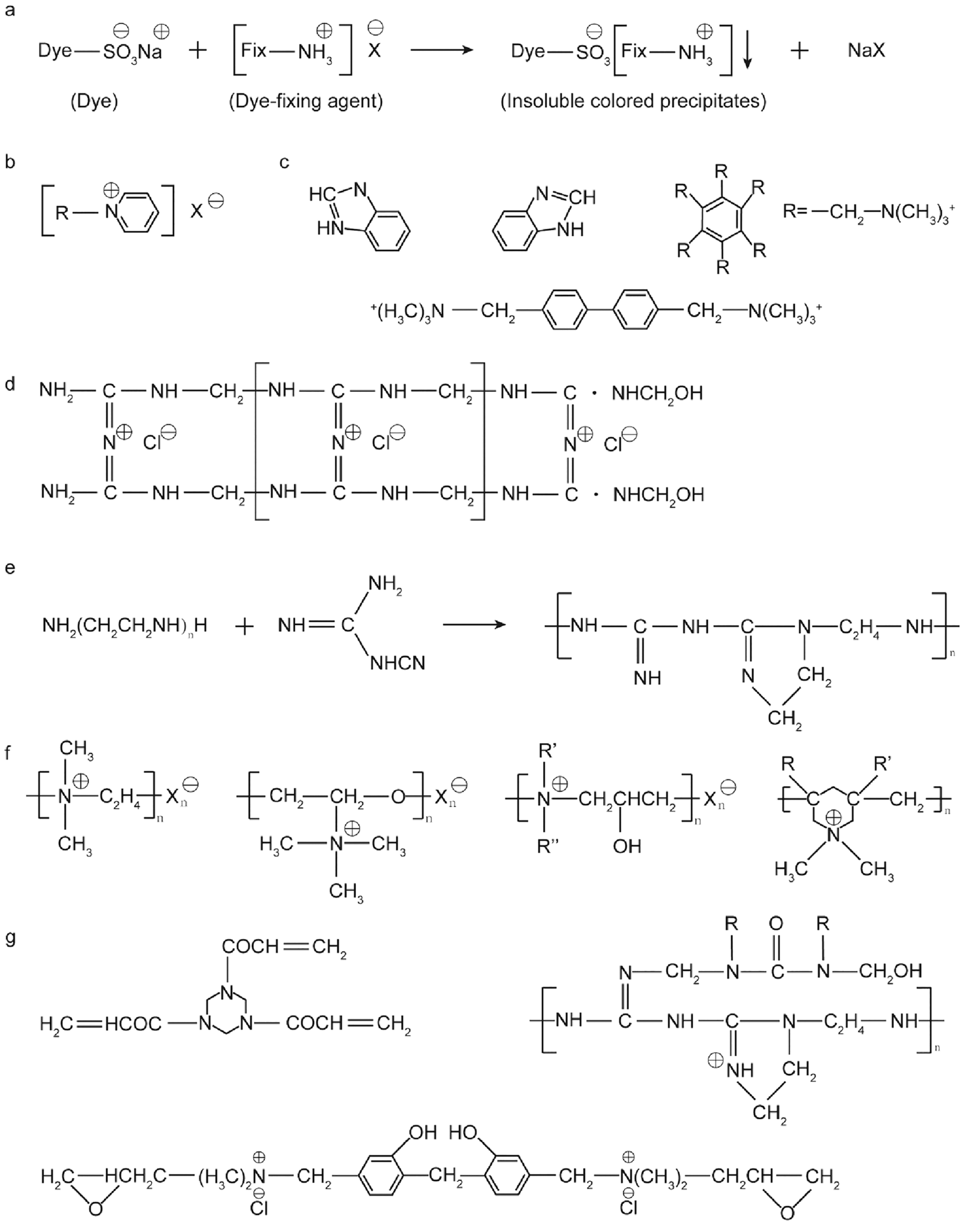


Fig. 4 **a** The reaction mechanism of dye-fixing agent, **b** structure of cationic pyridine quaternary ammonium salts, **c** structure of low molecular dye-fixing agent, **d** structure of color-fixing agent Y, **e** the reaction formula of polyamine dye-fixing agents, **f** several common molecular structural formulas of cationic polymer dye-fixing agent, **g** the typical molecular structure of reactive dye-fixing agent

the dye-fixing properties of PDMDAAC [31]. In the past 20 years, Japan has developed a variety of low-temperature and high-performance cationic dye-fixing agents. Their color-fixing temperature is 40–50 ℃, and the dosage is only half of the conventional color-fixing agent [23].

When active groups such as epoxides are introduced into the fixing agent, they can react with reactive groups on dye molecules and hydroxyl or amino groups on fiber molecules to form a highly diversified cross-linking system [32]. This kind of reactive dye-fixing agent can not only improve the color fastness of the fabric, but also enhance the antiwrinkle and antishrinkage properties of the fabric. The typical molecular structure is shown in Fig. 4g. Based on the research of these additives, a variety of cross-linking dyes have been synthesized and reported in recent years, which have greatly improved the color fastness of dyes [33–35]. In addition, when the ultraviolet absorber is incorporated into the molecule of dye-fixing agents, the ultraviolet absorption of the group in the light is used to prevent the damage of the ultraviolet on the dye structure, thereby enhancing sunlight fastness. For example, dibenzoyl ketones (such as benzoyl benzyl and benzoyl phenyl), salicylhydroxamic acids (such as salicylhydroxamic acid copper sodium salt), benzotriazole (including benzotriazole and benzotriazole sulfide), and phenoxyacetone (such as phenoxyacetone) are employed.

2.1.3 Thickening Agents

In the process of fabric printing, thickening agents are indispensable [36]. They not only thicken the color paste and reduce penetration, promoting adhesion, but also have an emulsifying effect, enhancing coloring capacity and brightness, thus giving the fabric clear patterns [37]. Low-molecular-weight thickening agents have simple formulation but exhibit unsatisfactory thickening effects, requiring large quantities and causing severe environmental pollution. In recent years, high-molecular-weight thickening agents, including natural polysaccharides (such as starch, cellulose, and sodium alginate) and synthetic polymers (such as polyacrylic acids, polyethylene glycol ethers, and polyethylene oxides), have been vigorously developed.

Although starch, as a thickening agent, has high paste-forming and coloring properties, it is difficult to wash away from the fabric surface, resulting in stiff hand feel and uneven color. Therefore, in the printing process, usually complementary auxiliaries such as dextrin and chitosan are added to improve the quality of printed fabrics [38, 39]. Furthermore, modified starch can significantly improve stability and solubility. For example, carboxymethyl starch can be used as a thickening agent for dispersion and reactive dye printing [40]. Carboxymethyl cellulose, hydroxyethyl cellulose, and methyl cellulose are commonly used cellulose-based thickeners. Carboxymethyl cellulose is suitable for K-type and KN-type reactive dye printing with high color yield, but poor hand feel [41, 42]. Methyl cellulose has good water solubility and is applied in polyester, wool, and silk printing [43]. Hydroxypropyl cellulose (HPC), poly(acrylic acid)-hydroxypropyl cellulose composite (poly (AA)-HPC), and their mixture in pigment printing paste also have also been intensively studied [44, 45]. Due to its good washability, high color yield, and soft hand feel of printed fabrics, sodium alginate is the most widely used natural thickener, suitable for printing with reactive, direct, dispersed, and acid dyes [37, 46, 47]. However, sodium alginate usually forms chelates with metal ions (Ca^{2+}, Al^{3+}, etc.), which may affect the quality of the printed products[48]. The use of sodium hexametaphosphate can prevent the precipitation of sodium alginate [23]. Table 1 compares the properties of natural polysugar printing thickeners.

Synthetic thickeners have become the preferred choice for industrial production due to their low cost, good stability, and minimal usage. Among them, polyacrylic acid thickeners exhibit optimal results, possessing high viscosity even at low solid contents. This can be attributed to the abundance of carboxyl groups present in the molecular chains, as well as the high degree of cross-linking existing between the main chains. Upon alkaline neutralization, the carboxylic acid groups not easily ionized are immediately transformed into ionized carboxylic ammonium or metal salt forms, resulting in electrostatic repulsion effects along the central anionic region of the copolymer macromolecules. This process leads to rapid expansion and extension of the macromolecules (Fig. 5). The local dissolution and swelling subsequently result in a significant increase in the viscosity of the printing paste.

The utilization of synthetic thickeners within the realm of textile printing yields a multitude of adverse ecological ramifications, encompassing unfavorable fabric properties, deleterious impacts on plumbing infrastructures, and environmental pollution. These unfavorable outcomes can be mitigated through the substitution of synthetic thickeners with natural thickeners that exhibit characteristics such as biodegradability, non-allergenicity, human non-toxicity, minimal waste treatment complications, and negligible safety apprehensions. Therefore, in recent years, the focus has returned to natural thickeners. Ibrahim et al. printed fabric samples (wool, silk, and nylon-6) with reactive dyes using new thickening agents based on polymerization adducts of acrylic acid with tamarind seed gum, or karaya gum [49]. Mongkholrattanasit et al. prepared a novel thickening agent from wild taro corms for the screen-printing of silk fabric with acid dye [50]. An attempt was made to print cotton fabric with pigments using a new thickening agent based on aloe vera polysaccharide gel [51, 52]. Saad et al. confirmed that adding metal salts to printing paste using aloe

Table 1 Comparison of properties of natural polysugar printing thickeners[a]

Printing paste	Color yield	Leveling property	Permeability	Fluidity	Easy cleaning
Starch	+++	++	–	Plastic fluid	–
Carboxymethyl starch	+++	+++	+	Plastic fluid ~ pseudoplastic fluid	+
Hydroxyethyl starch	–	++	+	Plastic fluid ~ pseudoplastic fluid	++~+++
Carboxymethyl cellulose	+++	+++	–	Pseudoplastic fluid	–
Methyl cellulose	+	+++	–	Pseudoplastic fluid	–
Arabic gum	+	+	+++	Newtonian fluid	+++
Dragon gum	+~++	+~++	+++	Quasi-Newtonian fluid	+++
Crystal gum	+	+++	+++	Newtonian fluid	+++
Locust bean gum	+	+	+++	Quasi-Newtonian fluid	+++
Hydroxyethyl locust bean gum	+	++~+++	+++	Quasi-Newtonian fluid	+++
Sodium alginate	+	+++	+++	Quasi-Newtonian fluid	+++

[a]+++ stands for excellent, ++ stands for good, + stands for average, – stands for poor

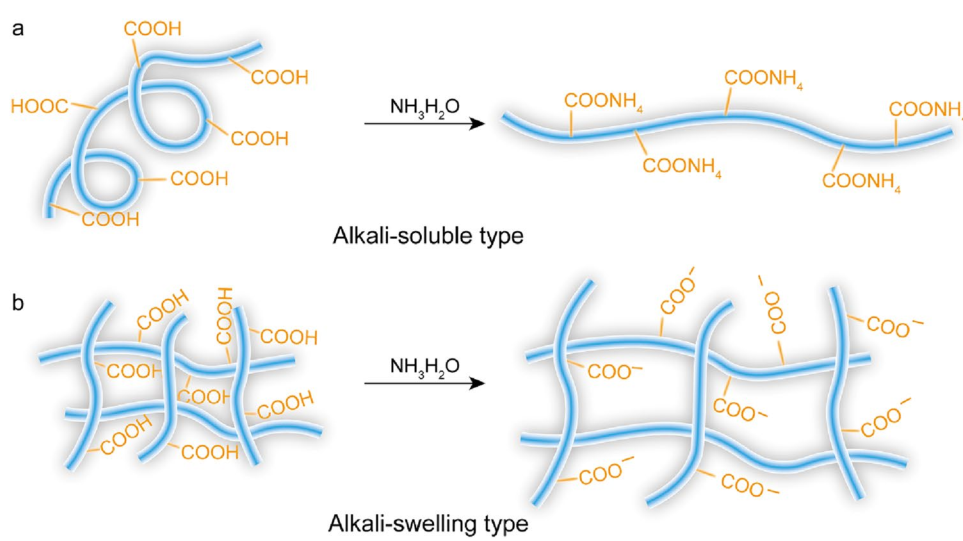
vera gel or flaxseed gum as thickener increases the whiteness index of these pastes as well as the printed fabric[53].

2.1.4 Binding Agents

Binding agents are effective bridging substances between fabric and pigment, which are widely used in textile printing [18]. Thermosetting binding agents, primarily composed of polyacrylic acid, undergo cross-linking reactions through baking to form a transparent film that encapsulates the pigments on the fiber surface. Zhou et al. chose polyacrylate as the waterborne adhesive in the printing paste system to greatly enhance structural stability, which was subsequently confirmed by laundering and rubbing tests [54]. Xing et al. prepared the polyacrylate microgel emulsion for improving the printing quality [55]. Ai et al. synthesized a water-based silicone-modified acrylate for adhesive coating of polyester. The superior color fastness (≥ level 4) with the low-emission printing process (residual dye concentration of 2.62 mg/L) was realized [56]. Gao et al. fabricated the epoxy-acrylate copolymer/nano-silica latex as the pigment printing binder and the resistance to wet rubbing fastness and soaping fastness of cotton fabric were improved half grade (Fig. 6a) [57].

Binder-free pigment printing of textiles is a type of environmentally friendly and clean production technology that is being actively promoted. Self-adhesive pigment is the key to achieve binder-free printing. Wang et al. prepared a series of fluorosilicone-modified polyacrylate/pigment hybrid latexes to explore how cross-linking degree affects film formation behavior and binder-free pigment printing performance on fabric [58]. Lu et al. successfully synthesized fluorosilicone modified polyacrylate/pigment (FSi-PAcr/PB) hybrid latex, which further improved the hand feeling, permeability, and water resistance of the pigment printed polyester fabrics(Fig. 6b) [59]. Li et al. synthesized an anionic poly (styrene-methyl methacrylate-acrylic acid)-absorbed

Fig. 5 Schematic diagram of the action principle of polyacrylic acid thickener: **a** alkali-soluble type, **b** alkali-swelling type



Rhodamine B (RB@PSMA) nanosphere via soap-free emulsion polymerization for printing the cotton fabrics without binders [60]. Yang et al. applied the self-adhesive polymer (PSBM-SP) latex particles based on spiropyran to obtain photochromic textiles with high fastness [61].

Conversely, thermoplastic binding agents (such as polyurethane) undergo softening or melting at elevated temperatures, resulting in mechanical entanglement or molecular penetration with the fabric surface, thereby achieving the adhesion purpose. Zeng et al. introduced trimethylolpropane to the polyurethane segment for synthesizing branched polyurethane [62]. The washing fastness of printed fabrics was at level 4, and the dry and wet rubbing rates were in the range of 3 and 2–3, respectively. Li et al. synthesized a series of acrylated epoxidized soybean oil-based UV-curable polyurethane pigment adhesives to reduce the consumption of energy and environment pollution in pigment printing process [63]. Mao et al. presented a work on the synthesis of blocked and branched waterborne polyurethane (BBPU) with polyurethane prepolymer, diethanol amine as a branching unit, and sodium bisulfite as a blocking agent [64]. A waterborne polydimethylsiloxane (PDMS)-modified polyurethane-acrylic (Si-PUA)/pigment hybrid emulsion was used as a self-curable hybrid pigment by Xie et al. to improve the air permeability and softness of printed fabric [65]. Compared with other transparent printing binding agents, polyurethane products do not cause screen-clogging problems because their prepolymers are water soluble.

2.1.5 Hydrophilic Finishing Agents

Although synthetic fibers exhibit excellent elasticity, high strength, and durability, their inherent hydrophobicity and poor moisture absorption result in inadequate antistatic properties, subpar wearing comfort, and limited stain resistance. The development of hydrophilic finishing agents brings significant benefits in terms of comfort, functionality, sustainability, and performance across a wide range of applications in textile industries. The function of hydrophilic finishing agents primarily relates to the wetting and spreading phenomena of water droplets on the surface of fibers. The diffusion coefficient (S) can be approximated by Eq. (1):

$$S = \gamma_f - \gamma_w, \tag{1}$$

S represents the diffusion coefficient, γ_f and γ_w are the respective surface tensions of the fiber and water (mN/m).

When $S > 0$, the surface tension of the fiber is greater than that of water, indicating wetting and spreading of water droplets on the fiber surface. In addition, due to the capillary nature of fibers, the action of hydrophilic finishing agents is also related to the capillary effect of the fibers. Assuming open-ended capillaries within the fabric, with one end immersed in water, a capillary pressure (P_c) is generated when equilibrium is reached. This is illustrated by Eq. (2) and Fig. 7a:

$$P_c = \frac{2\gamma_{fw}\cos\theta}{\rho g r} \tag{2}$$

P_c represents the capillary pressure, γ_{fw} is the interfacial tension between the fiber and water (mN/m), θ is the contact angle (°), r denotes the radius of the capillary (mm), ρ represents the density of water (g/cm^3), and g signifies the gravitational acceleration (m/s^2).

When $\theta < 90°$, h is greater than 0, indicating that water can spontaneously enter the capillary. Conversely, if $\theta > 90°$, it implies that water cannot be drawn into the capillary. Hydrophilic finishing agents significantly decrease the contact angle between synthetic fibers and water, thereby accelerating water penetration within the fabric.

Polyester-based hydrophilic finishing agents are water-based emulsions synthesized from the esterification and condensation reactions between dicarboxylic acids and diols. They are widely applied to hydrophilic finishing of polyester and its blends. These agents contain numerous hydrophilic groups that improve antistatic and wetting properties. Moreover, their ester-type structures are similar to those of polyester, making it possible for them to form co-crystalline or co-melt products with polyester fibers during heat treatment and therefore enhance durability [23]. Wang et al. added cationic groups to the traditional polyester hydrophilic agent, which further enhanced the hydrophilicity and fixation due to the cation–π interaction between the cationic groups and PET fabrics (Fig. 7b) [66]. Sun et al. reported a novel polyamide–polyether block copolymer (PPBC) and found that the hydrophilicity of polyamide fabric finished by PPBC had good washing fastness [67].

Another promising strategy of imparting hydrophilicity to synthetic fibers through the fixation of hydrophilic viscous substances has been pursued. Particularly, studies on the universal adhesion properties of polydopamine (PDA) inspired by mussel adhesion to various substrates have been widely reported. The PDA-modified PET showed a smooth surface and good hydrophilicity [68, 69]. PDA exhibits remarkable adhesive properties mainly due to the presence of functional groups such as phenolic hydroxyl and amine in its structure, which can undergo chemical reactions or form hydrogen bonds with various functional groups on surfaces, thereby achieving strong adhesion between polydopamine and diverse materials. Therefore, substances containing functional groups such as phenolic hydroxyl have also been demonstrated to possess similar adhesion and can be used for hydrophilic finishing of synthetic fibers. Cheng et al. created an amino-quinone network (AQN) coating on PET fabric via single-sided spraying of polyethyleneimine (PEI) and natural polyphenols, dopamine (DA), or tannic

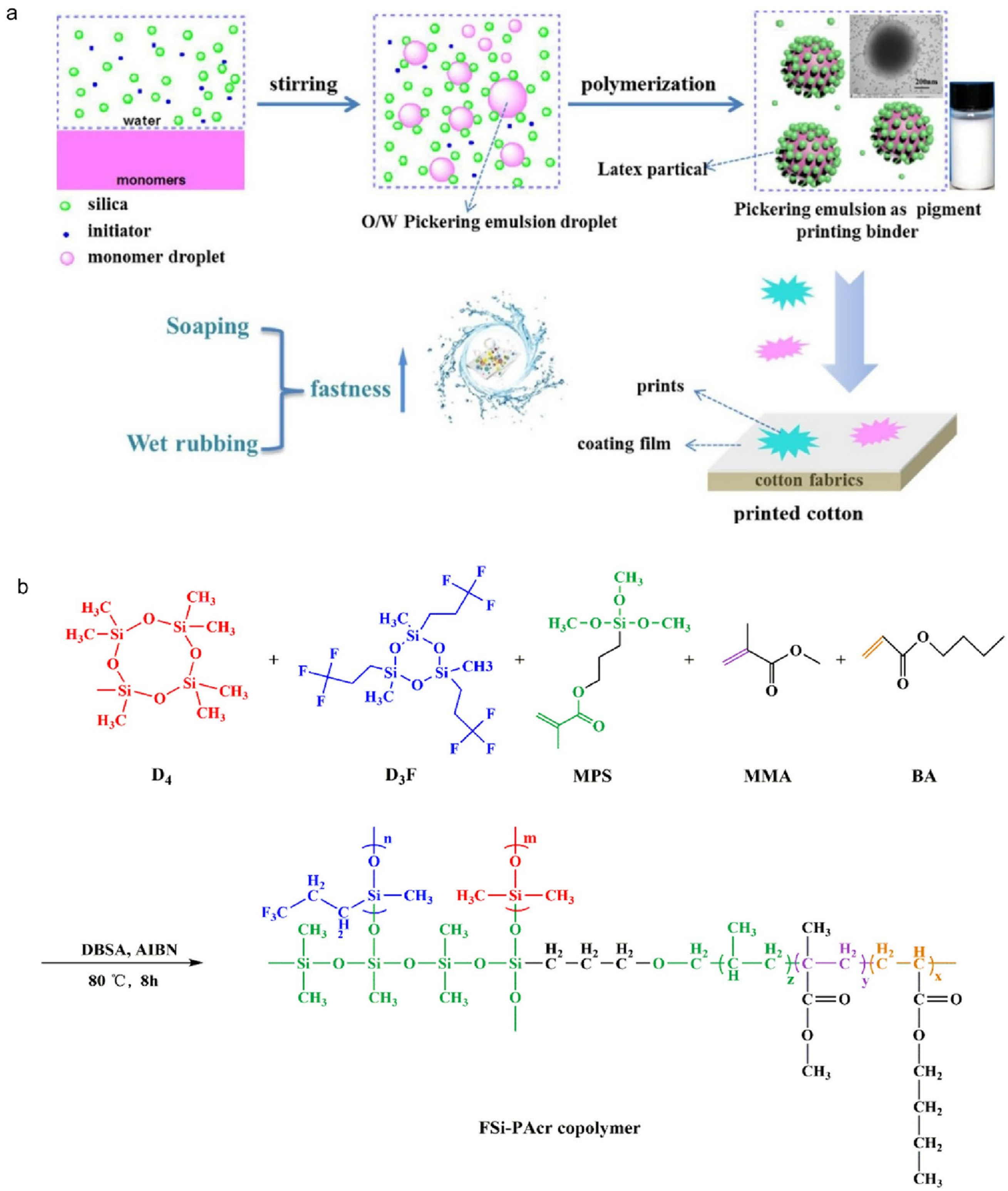


Fig. 6 **a** Diagram of the printing process of epoxy-acrylate copolymer/nano-silica latex as a pigment printing binder, reproduced with permission from Ref. [57], Copyright 2018, *Elsevier*, **b** Schematic diagram of reaction synthesis of FSi-PAcr copolymer, reproduced with permission from Ref. [59], Copyright 2021, *Wiley*

acid (TA) to obtain hydrophilicity [70]. Fu et al. successfully synthesized hydrophilic protein–polymer conjugates (Lyz-pSBMA) with exceptional adhesive properties using a grafting strategy (Fig. 7c) [71]. These conjugates endow textiles with easy-to-clean capabilities without compromising the wearer's comfort based on air and moisture permeability. Zhang et al. prepared a cellulose nanocrystal hollow microsphere (HM) coating for PET fabrics, which exhibited excellent film-formable ability, breathability, and moisture permeability [72]. Lou et al. carried out hydrophilic finishing of PET fabrics by applying chitosan and periodate oxidized β-cyclodextrin for wash resistance improvement [73]. In addition, hydrophilic finishing can also be achieved by fixing hydrophilic substances on the surface of fibers through synthetic adhesives. For example, Zaman et al. applied modified nanocrystalline cellulose to the surface of PET fabric using the textile adhesive PrintRite595® to achieve a hydrophilic finish [74].

2.1.6 Water- and Oil-Repellent Finishing Agents

In situations such as rainy weather or dining, textiles are generally expected to resist wetting and staining by oily substances. This is achieved by reducing the surface tension of the fabric below that of water (72.6 mN/m) or even oil (20–40 mN/m) through appropriate treatments. Fluorocarbon polymers have been widely employed over the past half-century due to their ability to endow textiles with water and oil repellency without compromising inherent breathability, moisture permeability, wearing comfort, and hand feel [75]. Three monomers are often present in fluorocarbon polymers: (1) Fluorinated monomers are essential for lowering the surface tension of fibers and contributing to their ability to repel water and oil. (2) The copolymer (butyl, lauryl, and octadecyl ester) can offer the finishing agent good film formation and softness while improving the fluorocarbon polymer's water resistance without lowering its oil resistance. (3) Cross-linked monomers, such as hydroxymethyl or epoxy groups found in acrylyl ester monomers, can generate strong bast films and enhance durability by self-cross-linking or cross-linking with fibers. It may also be a hydrophilic monomer (polyoxyethylene ether, sulfonyl group, etc.), providing the fabric easy decontamination properties.

The introduction of perfluoroalkyl (or potentially fully perfluoroalkyl) chains onto a non-fluorinated polymeric backbone (Fig. 8a) is typically achieved through chemical substances based on perfluoroalkanesulfonyl fluoride- or fluorotelomer-based chemistries [76]. These fluorinated side chains can be cleaved from the polymer chain, thereby releasing polyfluoroalkyl substances (PFASs). In response to increasing apprehensions surrounding the detrimental impacts of long-chain PFASs ($C_nF_{2n+1}SO_3H$, $n \geq 6$, and $C_nF_{2n+1}COOH$, $n \geq 7$) on human health and the environment, a substitution process has been initiated to replace long-chain PFASs with short-chain PFASs or non-fluorinated alternatives [77, 78]. Li et al. introduced octafluoropentanol as a short fluorocarbon chain and butyl acrylate and octadecyl acrylate as soft monomers into polyacrylates to replace the commercial long fluorocarbon chain water-repellent agent [79]. Lacruz et al. synthesized a series of fluorine-free, low-surface-energy, and partially bio-based (co)polymethacrylates, which provided the coated substrates with high static water contact angles as well as excellent solvent–water separation efficiencies [80]. Sharif et al. used citric acid, palmitic acid, succinic acid, and maleic acid to polymerize a few bio-based, fluorine-free oil and water repellents for cotton textiles [81, 82].

A similar water-repellent effect can also be achieved with polydimethylsiloxanes. Polydimethylsiloxane (PDMS) and poly(methylhydro)siloxane are the two most commonly used compounds. In PDMS, the oxygen atoms are masked by methyl groups, rendering them unapproachable to the hydrogen atoms in water [83]. As a result, the side methyl groups repel the hydrogen atoms in water molecules, thus achieving the desired waterproofing effect (Fig. 8b). Sheng et al. modified electrospun polyacrylonitrile (PAN) nanofibers with PDMS to achieve a delicate equilibrium between water resistance, breathability, and mechanical properties (Fig. 8c) [84]. Wu et al. proved that the titanium composite bamboo charcoal (TiO_2-BC) significantly improved the hydrophobic finishing effect of PDMS (Fig. 8d) [85]. Considering the combination of flame retardancy and water repellency of polysiloxanes, Dong et al. successfully synthesized a novel linear α,ω-di(chloro phosphoramide)-terminated polydimethylsiloxane (CPN-PDMS) and applied it to cotton fabrics [86]. Some studies have also shown that the introduction of polydimethylsiloxanes effectively improved the water repellency of waterborne polyurethane (WPU) [87, 88].

Despite the good water repellency and breathability conferred by polydimethylsiloxane-treated textiles, they suffer from poor wash resistance. Yu et al. fabricated a chemically bonded organic–inorganic nanohybrid cross-linked polysiloxane ($rSiO_2$–CAHPS) to ensure excellent washing resistance of cotton fabrics (Fig. 8e) [89]. The reliability of this method has also been verified by other researchers [90, 91]. Furthermore, compared to PDMS, polymethylhydrosiloxane has superior washable resistance. This is due to the fact that part of Si–H is converted into Si–OH under the action of high temperature and catalyst. A mesh film is formed when one portion of Si–OH interacts with Si–H, while another part of Si–OH cross-links with the hydroxyl group on the fiber [23].

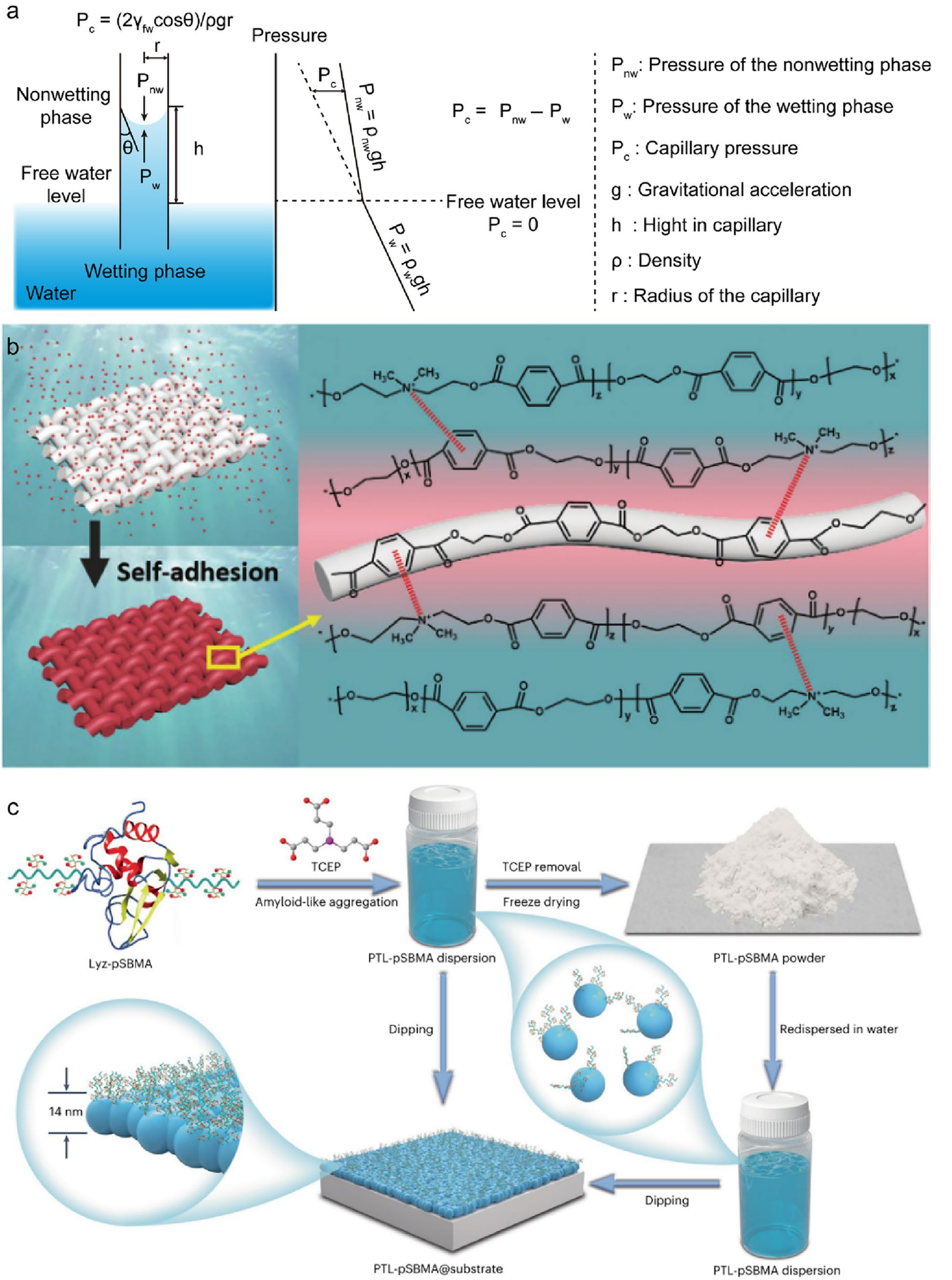

a
Pc = (2γfwcosθ)/ρgr
r
Pnw
Nonwetting phase
θ
h
Free water level
Pw
Wetting phase
Water
Pressure
Pc
Pnw = ρnwgh
Pc = Pnw − Pw
Free water level
Pc = 0
Pw = ρwgh
Pnw: Pressure of the nonwetting phase
Pw: Pressure of the wetting phase
Pc : Capillary pressure
g : Gravitational acceleration
h : Hight in capillary
ρ : Density
r : Radius of the capillary
b
Self-adhesion
c
Lyz-pSBMA
TCEP
Amyloid-like aggregation
PTL-pSBMA dispersion
TCEP removal
Freeze drying
PTL-pSBMA powder
Dipping
Redispersed in water
14 nm
Dipping
PTL-pSBMA@substrate
PTL-pSBMA dispersion

Fig. 7 **a** Diagram of capillary pressure (P_c), **b** diagram of the cation–π interaction between the cationic groups and PET fabrics, reproduced with permission from Ref. [66], Copyright 2021, *Wiley*, **c** preparation and application of the hydrophilic protein–polymer conjugates (Lyz-pSBMA), reproduced with permission from Ref. [71], Copyright 2023, *Springer Nature*

2.1.7 Anti-static Finishing Agents

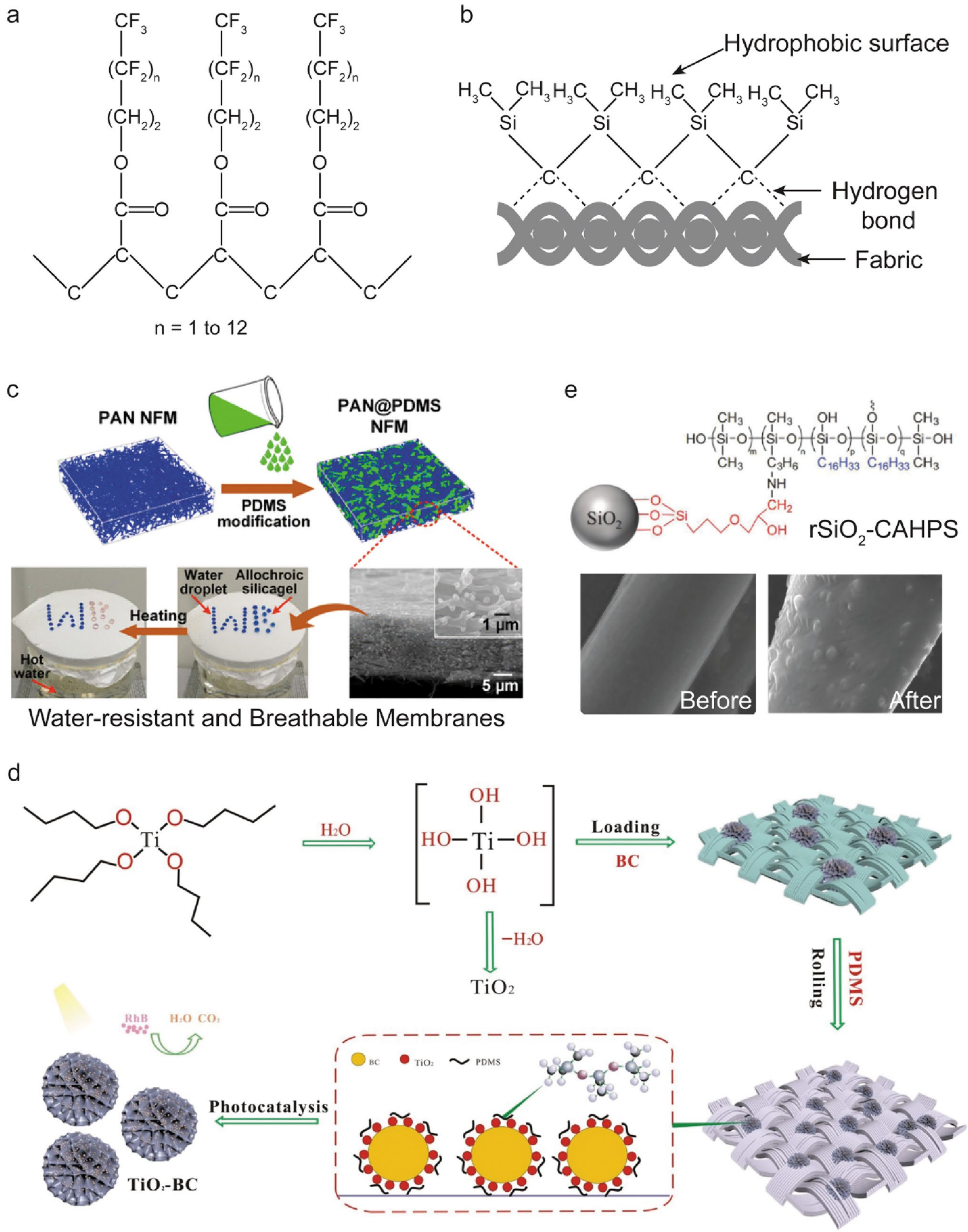
During the processing and usage of textiles, static electricity can be easily generated through contact or friction [92]. As most textiles are poor conductors, static accumulation occurs frequently [93]. This not only complicates fiber processing but also leads to the attraction of dust particles and discomfort during wear [94]. The principle of antistatic finish primarily focuses on two aspects: (1) reducing fiber friction to inhibit static generation and (2) enhancing the rate of static dissipation. Effective methods for achieving antistatic effects in textiles involve the addition of lubricants to minimize friction and the adsorption of antistatic agent molecules to lower the surface resistance of fibers. Non-durable antistatic agents typically consist of surfactants, such as alkyl sulfates, quaternary ammonium salts, and fatty alcohol polyoxyethylene ethers. These agents readily bind to the hydrophobic groups on the fiber surface while forming outward hydrophilic conductive layers, thereby mitigating static accumulation [23]. However, fabrics treated with non-durable agents generally exhibit limited durability in household washing, resulting in their limited current applications. In contrast, durable antistatic agents usually comprise polymers with hydrophilic or ionic groups that form long-lasting films on the fiber surface or undergo cross-linking reactions with fibers. Fabrics treated with durable agents maintain excellent antistatic performance even after undergoing more than 15 washing cycles.

The development and utilization of polymeric materials have shown great potential in effectively mitigating static accumulation in textiles. Through comprehensive investigations into their structure–property relationships, researchers have sought to optimize the antistatic performance of these polymers by tailoring their chemical composition, molecular architecture, and processing techniques. Quan et al. studied a foam-coating process based on polyurethanes, endowing cashmere with pilling resistance and static resistance from bottom coating and table coating, respectively [95]. Yang et al. improved the antistatic properties of cashmere fabric by introducing an antistatic agent consisting of cationic waterborne polyurethane and graphene-cellulose nanocrystalline [96]. Xu et al. investigated the effect of fiber stretching on the conductive layer and revealed the underlying mechanism [97]. As depicted in Fig. 9a, the fiber treated with organic antistatic agent (OAA) exhibited low surface energy, hindering the formation of a continuous conductive layer of water molecules on the crimped fiber surface. However, stretching the OAA-treated fiber enabled disconnected water molecules to form a thin, continuous conductive layer, leading to a significant reduction in resistivity. Conversely, the sulfonated carbon nanotubes (SCNTs)/OAA-treated fiber had high surface energy, facilitating the formation of a continuous conductive layer of water molecules on the crimped fiber surface. Moreover, the physical conductive network formed by SCNTs remained unaffected during the stretching process. Basuoni et al. treated acrylic fabrics with the cysteine/biopolymer system by pad-dry-cure method, and the fabrics were durable to washing for up to 20 washing cycles in terms of wettability and antistatic property due to amide bond formation [98]. In addition, the loading of natural polymers with excellent hygroscopic properties or onto the fabric also reduces the accumulation of static electricity. For example, Zhao et al. constructed a copper ion-cross-linked sodium alginate-graphene oxide (Cu^{2+}/SA-GO) structure on the nylon 66 fabric with PDA-mediated layer-by-layer self-assembled technology (Fig. 9b) [99]. The advancements in polymer synthesis and modification techniques have facilitated the creation of durable antistatic agents that can withstand repeated washing and extended usage without compromising their efficacy.

2.1.8 Anti-UV Finishing Agents

UV radiation within the range of 200–400 nm can induce various skin conditions such as erythema, pigmentation, aging, and even carcinogenesis [100, 101]. Employing UV-resistant textiles as a protective measure is pivotal in mitigating the detrimental effects of UV exposure [102]. There are two approaches to preparing UV-resistant textiles: (1) incorporating antiultraviolet finishing agents into polymer spinning solutions and (2) applying UV-resistant finishing agents onto fabrics via padding or coating.

Antiultraviolet finishing agents encompass UV absorbers and UV scatterers. UV absorbers possess the ability to absorb UV radiation and transform it into heat or low-energy radiation, typically utilizing organic compounds such as salicylates, benzophenones, and benzotriazoles [103]. For instance, under illumination, the excited carbonyl group within benzophenone compounds becomes unstable, readily abstracting hydrogen atoms from neighboring phenolic hydroxyl groups, thereby generating an enol and releasing surplus energy. Subsequently, the molecular structure of benzophenone reverts back through intramolecular enol–ketone tautomerism (Fig. 10a) [104]. He et al. found that the antiultraviolet properties of cotton were improved by dyeing with dyes containing a built-in hydroxybenzophenone moiety


a
n = 1 to 12
b
Hydrophobic surface
Hydrogen bond
Fabric
c
PAN NFM
PAN@PDMS NFM
PDMS modification
Water droplet
Allochroic silicagel
Heating
Hot water
1 μm
5 μm
Water-resistant and Breathable Membranes
e
rSiO2-CAHPS
Before
After
d
H2O
Loading
BC
−H2O
TiO2
Rolling
PDMS
BC
TiO2
PDMS
Photocatalysis
RhB
H2O CO2
TiO2-BC

◂**Fig. 8** **a** Acrylic backbone of perfluorinated compounds, **b** mechanism diagram of binding mode between polydimethylsiloxane water-repellent finishing agent and fiber, **c** water-resistant and breathable PAN@PDMS membranes, reproduced with permission from Ref. [84], Copyright 2016, American Chemical Society, **d** preparation flowchart of TiO_2-BC, reproduced with permission from Ref. [85], Copyright 2021, *Elsevier*, **e** the structure of $rSiO_2$–CAHPS and the surface morphology of cotton fabric before and after treatment, reproduced with permission from Ref. [89], Copyright 2021, MDPI

and it was not necessary for the benzophenone ultraviolet absorber to be chemically bonded to the dye molecules [105]. Xiao et al. used a 3D-QSAR model to screen benzophenone-type (BP) UV absorbers with high light absorption, low permeability, and low toxicity [104]. Simultaneously, it was emphasized that the impact of BP molecules is significantly influenced by their charge distribution. The alteration in electron transition properties, excited state transition dipole moment, and variance in electron transfer characteristics between ground and excited states played crucial roles in augmenting the UV absorption capacity of BP molecules (Fig. 10b). However, BP exhibits multiple toxicological effects such as environmental persistence, potential bioaccumulation, and acute toxicity to aquatic organisms, which hinders its promising prospects [104].

In recent years, there has been a keen interest in the development of naturally derived plant antimicrobial agents that are both safe and environmentally friendly [102]. Zhang et al. reported that the PVA/tea polyphenols (TP) composite with only 5% TP shows superb anti-UV properties even after water washing [106]. Zheng et al. prepared a natural plant antiultraviolet finishing agent containing amaranthus purslane, solanum annuum, and phellodendron cedar, and the ultraviolet protection factor (UPF) of cotton fabric treated with optimum proportion was 61.02% [107]. Shi et al. proposed that the ozonated enzymatic lignin grafted to polyethylene glycol (OzEL-PEGs) afforded satisfactory UV-absorbing properties (Fig. 10c) [108]. Ding et al. obtained the conclusion that the addition of the α-truxillic acid monomer effectively improved the ultraviolet-shielding performance of poly (ethylene terephthalate) (Fig. 10d) [109].

The other category of UV-scattering agents primarily consists of metal oxides, with zinc oxide (ZnO) and titanium dioxide (TiO_2) being the most extensively studied. These agents leverage their inherent physical properties to scatter, reflect, and block UV radiation, thereby inhibiting its penetration through fibers. ZnO is capable of shielding UV radiation within the wavelength range of 240–380 nm, while TiO_2 effectively blocks UV radiation in the wavelength range of 340–360 nm. Wang et al. incorporated ZnO nanoparticles into nanofibers to give the fabric stable and excellent UV resistance [111]. Kaur et al. summarized and discussed in detail the development of lignin-based ZnO and TiO_2 composites for UV protective applications [112]. Zhang et al. developed the aramid fiber with coordination of ZnO by a facile supercritical CO_2 drying technique to improve its UV resistance and interfacial adhesion (Fig. 10e) [110].

There is a growing demand for antiultraviolet finishing agents that offer enhanced durability and long-lasting effectiveness, as consumers seek reliable and sustainable solutions for sun protection in textiles. The focus is shifting toward the development of eco-friendly and non-toxic antiultraviolet agents, utilizing natural and biodegradable materials, to address environmental concerns and meet regulatory requirements. Furthermore, fabric composites incorporating metal–organic frameworks (MOFs) demonstrate potential as efficient UV-protective materials. Emam et al. reported that the UPFs of MIL-68(In)-NH_2 and MIL-125(Ti)-NH_2 MOF@textile composites were greater than 30 even with lower MOF content[113]. Li et al. created a UV-shielding CuBTC@cotton fabric with a UPF of 170 [114]. Advancements in nanotechnology and functional textiles are driving the innovation of antiultraviolet finishing agents with improved breathability, flexibility, and comfort, catering to the diverse needs of consumers across industries.

2.2 Sustainability

2.2.1 Policy Orientation and Market Demand

Water is one of the most crucial resources for the survival and development of human society [115–117]. According to statistics, approximately 1.8 billion people worldwide lacked access to safely managed drinking water in 2020 (Fig. 11a, b) [118]. By 2050, more than half of the global population may face water scarcity [119–121]. The textile industry ranks second in terms of water consumption, with textile wastewater accounting for 20% of total industrial wastewater [122]. Auxiliary agents play a vital role in reducing water usage in textile production and daily care practices, but at the same time, they also increase the difficulty of wastewater treatment. The use of subpar auxiliaries often results in elevated levels of dissolved solids, biological oxygen demand (BOD), and chemical oxygen demand (COD) in the effluent. In 1997, the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (referred to as the "Water Convention") and the Convention on the Non-Navigational Uses of International Watercourses (referred to as the "Watercourses Convention") were adopted at the United Nations General Assembly. These conventions aim to promote the management and sustainable utilization of transboundary watercourses.

In addition, global warming has garnered significant attention due to its severe threats to ecosystems, economy, culture, and more [124–126]. The primary cause of global warming is the extensive use of fossil fuels such as coal and petroleum by humans over the past century, resulting

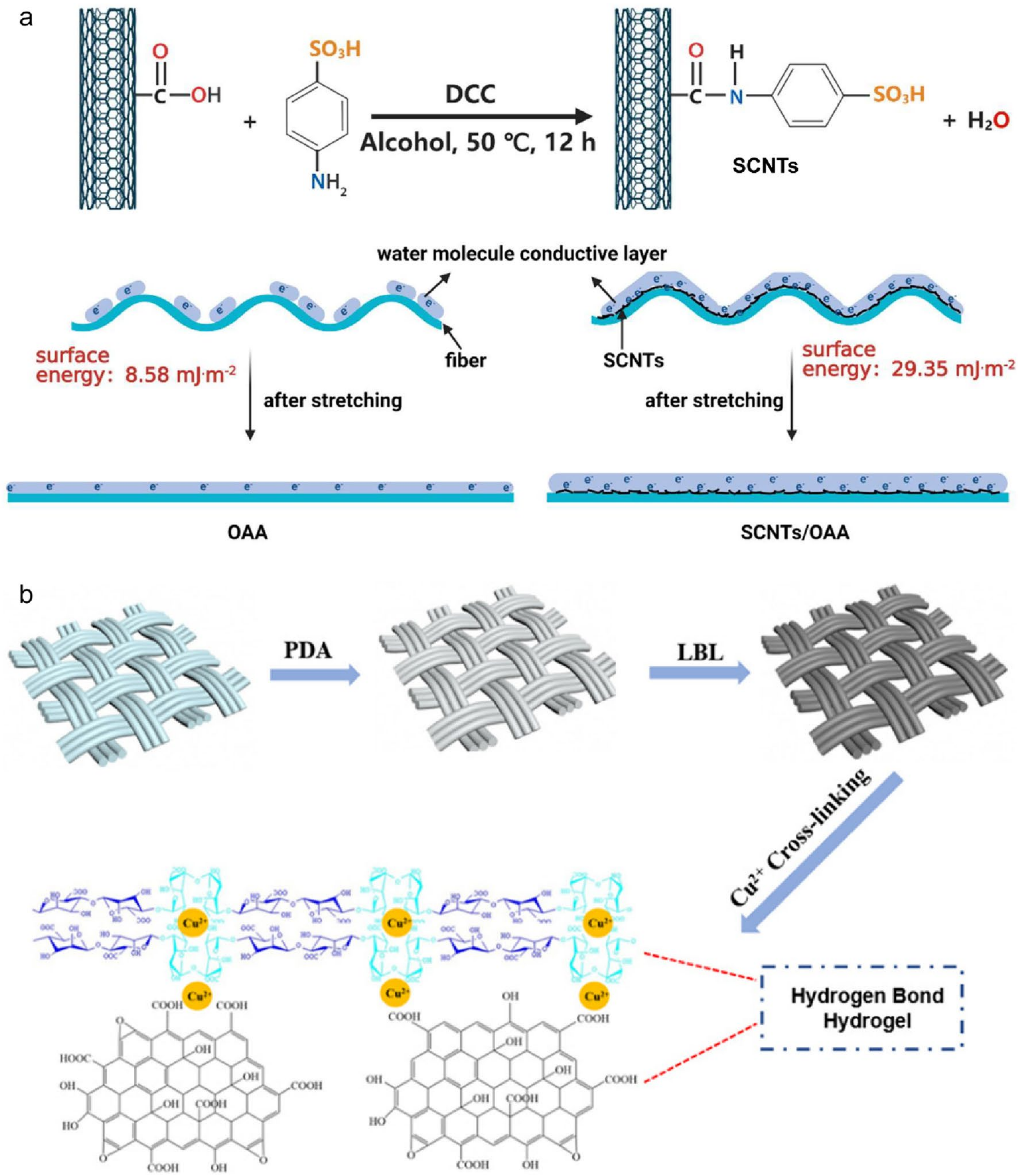


Fig. 9 **a** Antistatic mechanism diagram during the stretching process, reproduced with permission from Ref. [97], Copyright 2021, MDPI, **b** schematic diagram of Cu^{2+}/SA-GO loaded onto nylon 66, reproduced with permission from Ref. [99], Copyright 2022, *Elsevier*

in a sharp increase in carbon emissions. In 2015, countries worldwide reached the Paris Agreement to address climate change, symbolizing a global shift toward green and low-carbon transformation and representing the minimum actions needed to protect our planet. Building upon the Paris Agreement, the United Nations Climate Change Conference in 2021 further emphasized the goal of limiting global temperature rise to 1.5 °C and achieving global carbon neutrality by the latter half of the twenty-first century [127, 128]. David et al. provided predictive results (Fig. 11c) for annual GDP, population, and greenhouse gas emissions spanning multiple centuries [123]. However, even under the best-case scenario predicted by the models, it could not guarantee limiting global warming to 2 °C [129, 130]. Non-carbon dioxide greenhouse gas emissions pose a significant uncertainty factor [131, 132].

The textile industry encompasses various stages throughout its lifecycle, including raw material cultivation, textile material research and development, textile processing, wholesale, and sales. These stages contribute to carbon emissions, accounting for approximately 1.2 billion tons or 5–10% of global carbon emissions [133]. Apart from oil and gas, the entire lifecycle of textiles is considered one of the most wasteful and polluting periods. These statistical findings clearly contradict the principles of the United Nations' 2030 Agenda for Sustainable Industrialization and global climate governance goals. In 2020, China announced its intention to enhance its national contributions, aiming to reach the peak of carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. Reducing carbon emissions in the textile industry can have a significant impact on climate change. Upgrading and iterating textile auxiliaries is one effective approach toward achieving a greener and low-carbon textile industry. On the one hand, high-quality auxiliaries can effectively reduce processing temperatures and time for textile treatments. On the other hand, they require lower quantities to achieve the same processing results, thus alleviating the pressure on wastewater, exhaust gases, and solid waste management. Therefore, in response to the United Nations' call for preserving water resources and reducing carbon emissions, it is crucial for the textile industry to vigorously pursue the development of high-quality auxiliaries as part of its green transformation efforts.

Recently, there has been an increased awareness regarding the ecological hazards associated with some highly effective textile auxiliaries [134]. The rigid commodity value of textiles is no longer the sole criterion for selection, and there is a growing focus on satisfying the subjective value that people seek. For example, green and low-carbon products can meet not only consumers' basic needs but also their demands for environmental friendliness and sustainability. Accordingly, during the production and processing stages, significant consideration should be given to environmentally friendly and low-carbon textile auxiliaries.

2.2.2 Green Textile Auxiliaries

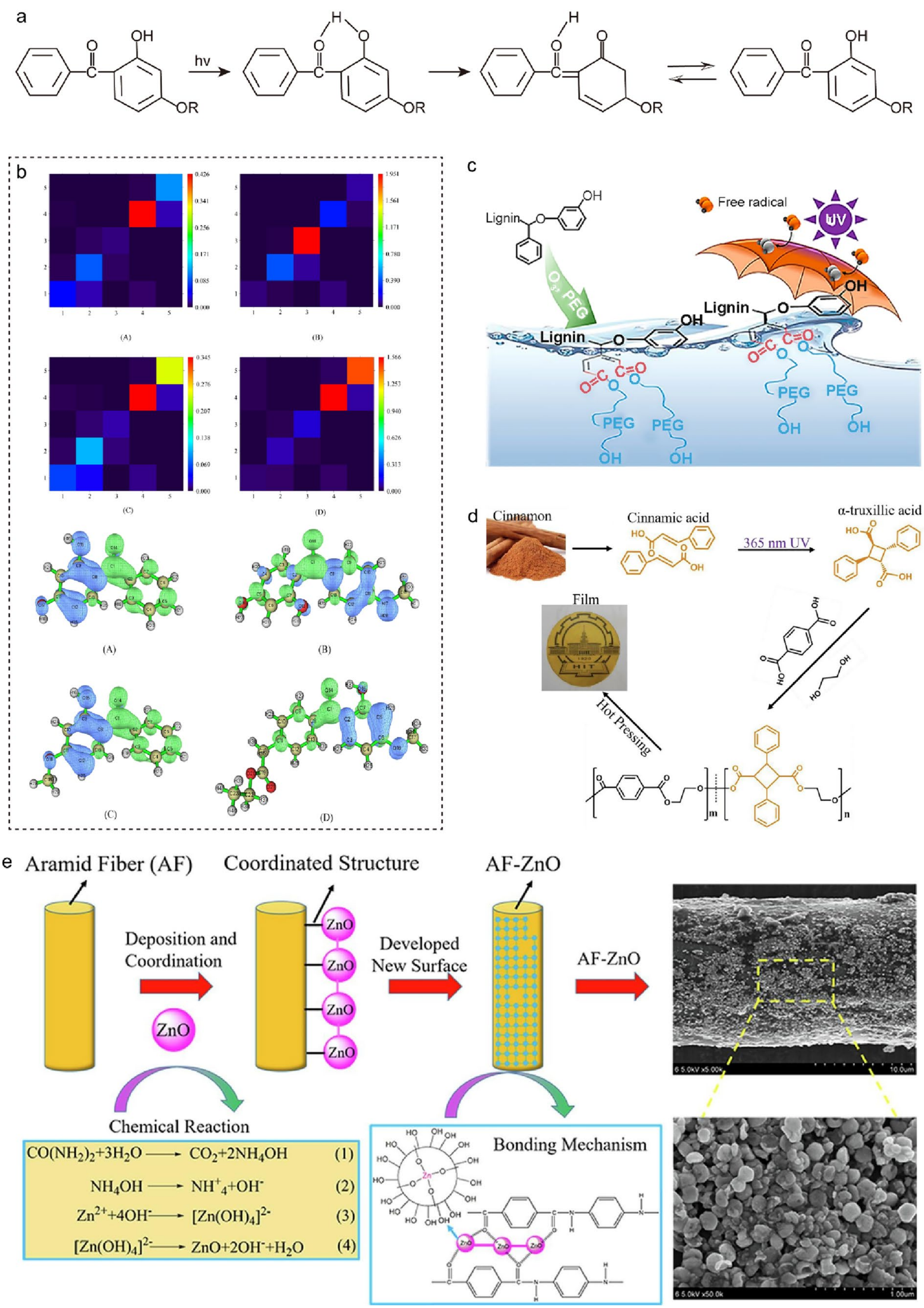
The research on green textile auxiliaries constitutes a crucial aspect of sustainable development in the textile industry. One key area of focus will be the exploration and utilization of alternative raw materials. Researchers will investigate the feasibility of using bio-based materials derived from renewable sources as substitutes for traditional petroleum-based chemicals. For example, starch constitutes approximately 70% of the total size used in China [135]. Plant-based anti-ultraviolet finishing agents have been described previously. Furthermore, green textile auxiliaries usually involve their biodegradability and ecotoxicity profiles. Non-toxic and degradable auxiliaries have emerged as a promising solution in mitigating the environmental impact of textile production. These auxiliaries possess the ability to undergo microbial oxidation and decomposition, ultimately transforming into harmless by-products such as carbon dioxide, water, and inorganic elements. By utilizing the natural processes of microorganisms, degradable auxiliaries offer a sustainable pathway for reducing the accumulation of persistent pollutants in the environment.

As mentioned above, PVA is a widely used sizing agent due to its exceptional sizing performance and ease of removal. Despite these advantages, PVA poses a significant challenge in terms of its environmental impact as it does not degrade in conventional textile effluent treatment plants. To address this issue, efforts have been made to minimize the environmental effects of PVA by replacing it with biopolymers. For example, the modification of starch-based sizing agents enhances their compatibility with synthetic fiber and their blends' sizing applications [136–138]. The application of cyclodextrins as sizing agents for carbon fibers, natural fibers, and synthetic fibers has been extensively studied [139–141]. Their unique molecular structure and host–guest complexation properties provide numerous benefits, including improved adhesion, controlled release, and environmental sustainability. Chitosan, derived from chitin, is a promising sizing agent in fabric production due to its biodegradability, adhesion improvement, and antimicrobial properties [142, 143]. Furthermore, plant proteins such as soy proteins and wheat gluten and chicken feathers have also been studied as alternative sizing agents to PVA [144–146].

During the pretreatment process, hydrogen peroxide and enzyme preparations are two prominent types of biodegradable textile auxiliaries. As previously discussed in detail, the use of biodegradable textile auxiliaries has become increasingly popular due to their low environmental impact. However, it is important to note that the correct use of these chemicals is essential to ensure their safety and effectiveness. Therefore, it is necessary to continue researching and developing new biodegradable pretreatment auxiliaries to further reduce the environmental footprint of the textile industry.

During the process of dyeing, Kalapriya et al. successfully extracted seven types of biodegradable dye-fixing agents from plants (mango leaf, tulasi leaf, vembu leaf, karisalankanni leaf, banana stem, pomegranate seeds, and neat tender coconut liquid) [147]. The result showed that mango leaf, karisalankanni leaf, and banana stem exhibited better dye-fixing behavior than that of others. In the printing process, the properties of natural polysugar printing thickeners have been compared in the previous section.

In recent years, there has been a notable surge in the utilization of an extensive array of biodegradable finishing agents for textile functional enhancement. Natural polymers, such as chitosan, alginate, starch derivatives, and cellulose enzymes, have been widely used as biodegradable finishing


a
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hv
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Lignin
PEG
OH
d
Cinnamon
Cinnamic acid
365 nm UV
α-truxillic acid
Film
Hot Pressing
m
n
e
Aramid Fiber (AF)
Coordinated Structure
AF-ZnO
Deposition and
Coordination
ZnO
Developed
New Surface
AF-ZnO
Chemical Reaction
CO(NH2)2+3H2O ⟶ CO2+2NH4OH (1)
NH4OH ⟶ NH+4+OH- (2)
Zn2++4OH- ⟶ [Zn(OH)4]2- (3)
[Zn(OH)4]2- ⟶ ZnO+2OH-+H2O (4)
Bonding Mechanism

◂**Fig. 10** **a** UV absorption principle of benzophenone compounds, **b** transition dipole moment matrix heatmap of BP molecules and excited state hole-electron distribution of BP molecules, reproduced with permission from Ref. [104], Copyright 2021, *Elsevier*, **c** schematic illustration of OzEL-PEGs as an antiultraviolet finishing agent, reproduced with permission from Ref. [108], Copyright 2020, American Chemical Society, **d** synthesis diagram of ultraviolet-shielding poly(ethylene α-truxillate-co-ethylene terephthalate), reproduced with permission from Ref. [109], Copyright 2019, *Elsevier*, **e** schematic illustration of aramid fiber (AF) with coordination of ZnO, reproduced with permission from Ref. [110], Copyright 2020, *Elsevier*

agents for textiles due to their excellent biocompatibility and biodegradability. The application of lipase and esterase enzymes in PET-based textiles has been demonstrated to be an effective approach for enhancing surface softness and moisture absorption qualities [148]. Biopolishing, which involves the use of cellulose enzymes to remove loose fibers from cotton fabric, has also been widely employed in the textile industry [149]. In addition, wool has been rendered shrink-proof through the enzymatic reaction of plant-based papain enzyme, which breaks down the protein structure responsible for wool shrinkage [150]. Natural antibacterial agents and antiultraviolet finishing agents have received much attention. Synthetic biodegradable polymers, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), clearly show great potential as biodegradable finishing agents for textiles due to their tunable properties [151, 152]. The development and application of these biodegradable finishing agents have contributed to the sustainable development of the textile industry and promoted more environmentally friendly practices.

Moreover, polyester currently reigns as the predominant fiber of choice, yet its biodegradation in the natural environment poses a formidable challenge. Several studies have emerged focusing on the biological degradation of PET, which highlight the involvement of filamentous fungi such as *Fusarium oxysporum* and *F. solani* [153, 154], as well as the bacterium *Ideonella sakaiensis* [155]. These studies have made positive contributions to the resource utilization of polyester waste and the reduction of environmental pollution and also provided reference and inspiration for solving other synthetic fiber waste treatment.

3 The Main Problems Faced by the Textile Auxiliary Industry

3.1 Market Competitiveness Problems

The market competitive issues in the textile auxiliary market are characterized by low industry concentration, intensified homogeneous competition, and poor efficiency. These factors contribute to a highly fragmented market with multiple competitors lacking dominant market shares, a focus on price-based competition due to limited product differentiation, and a large benefit gap between leading international enterprises. In response to these challenges requires comprehensive strategies aimed at enhancing industry consolidation, promoting innovation-driven competition, and improving operational effectiveness throughout the value chain.

Low industry concentration in the textile auxiliary market indicates the presence of multiple competitors without dominant companies holding significant market shares. This may lead to intense market competition, with frequent occurrences of price wars and other competitive strategies among suppliers. The reasons for low industry concentration in the textile auxiliary market may include a large number of small- and medium-sized enterprises, low barriers to entry, and weak industry regulation. To address this issue, efforts can be made to encourage consolidation and mergers among smaller enterprises to create larger, dominant firms. In addition, policymakers can introduce measures such as industry regulations and incentives for industry players to collaborate on research and development to foster a more collaborative and competitive market environment.

Intensified homogeneous competition in the textile auxiliary market refers to the high similarity among products or services offered by different suppliers, lacking apparent differentiation. This may result in price becoming the primary means of competition rather than focusing on aspects such as technological innovation, product quality, or customer service. To solve this problem, strategies can be implemented to differentiate products or services through technological innovations, product diversification, and value-added features. In addition, efforts can be made to enhance customer relationships, improve brand image, and establish strong distribution networks to create competitive advantages beyond pricing considerations.

Poor efficiency in the textile auxiliary market indicates the presence of various inefficiencies in both production and operational processes. These inefficiencies can be attributed to factors such as suboptimal supply chain management practices, imperfect manufacturing processes characterized by bottlenecks or substandard quality controls, as well as low levels of resource utilization efficiency resulting from inadequate planning or utilization of available resources. Addressing these inefficiencies requires interventions aimed at enhancing supply chain coordination, optimizing manufacturing processes, and improving resource management practices to achieve higher levels of efficiency and productivity in the textile auxiliary market.

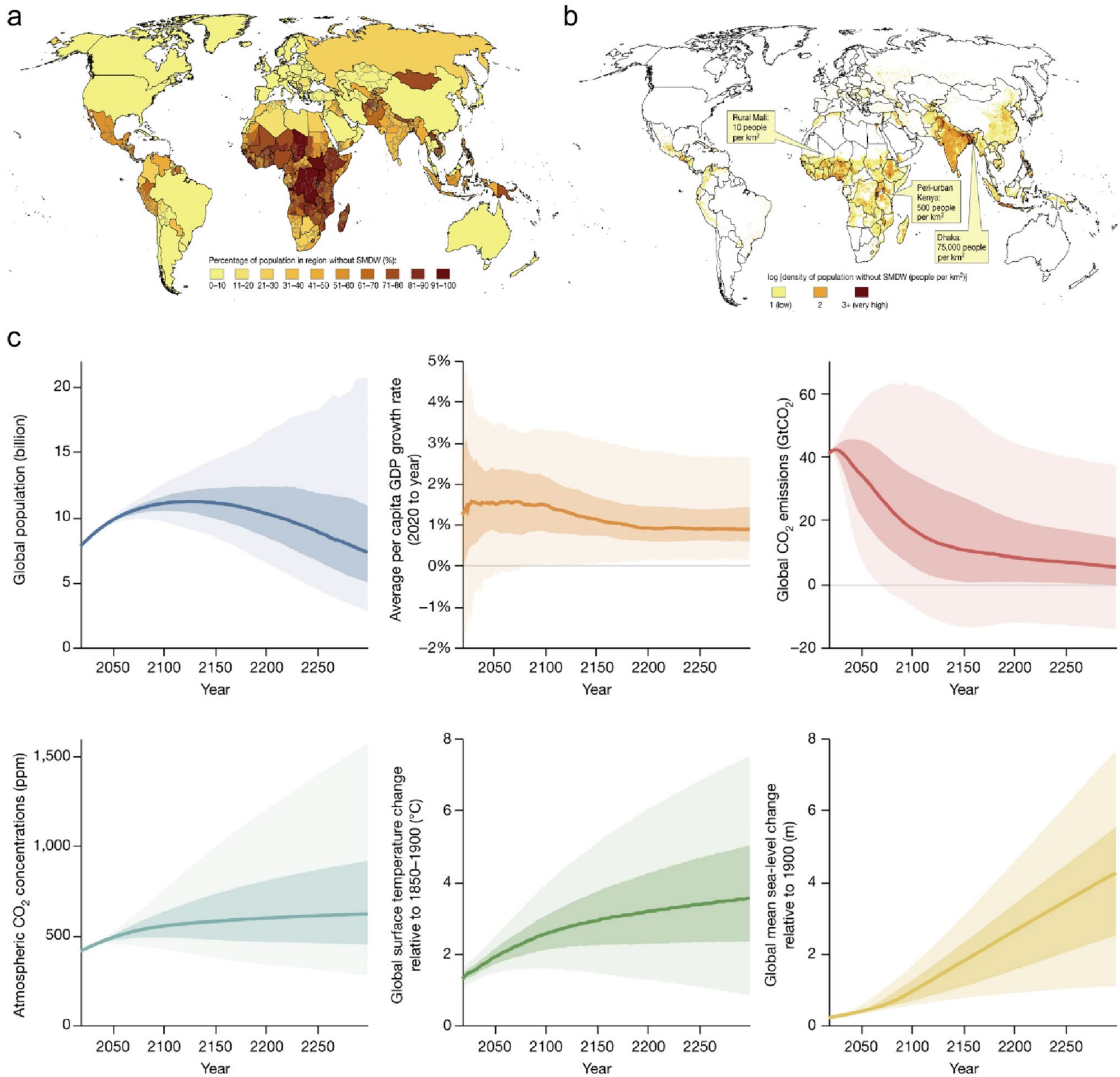


Fig. 11 **a** Percentage of population in region without SMDW as reported by the WHO/UNICEF JMP, reproduced with permission from Ref. [118], Copyright 2021, *Springer Nature*, **b** log population density of people without SMDW from WorldPop at 1 km resolution adjusted by JMP proportions at 1 km resolution, reproduced with permission from Ref. [118], Copyright 2021, *Springer Nature*, **c** RFF-SP socioeconomic scenarios and the resulting climate system projections, reproduced with permission from Ref. [123], Copyright 2022, *Springer Nature*

3.2 Environmental Problems

As mentioned above, the textile chemical industry faces several environmental challenges. First, the non-standard discharge of wastewater in the production and use of textile auxiliaries can easily cause water pollution. Second, volatile organic compounds and greenhouse gas emissions are important sources of air pollution and climate change, respectively. In addition, improper disposal of solid waste may lead to soil and groundwater pollution.

Addressing these environmental challenges requires a multifaceted effort. First of all, the use of clean production technologies, such as salt-free dyeing, less water dyeing, and water-free printing, can minimize the emission of pollutants.

Second, establishing a more stringent regulatory system and improving wastewater standards, carbon emission limits, and waste disposal regulations. Third, encouraging sustainable production practices, such as the recycling and reuse of wastewater and energy, to minimize environmental harm and reduce dependence on resources. Finally, popularizing environmental protection auxiliaries, such as biodegradable, non-toxic, and low-toxic auxiliaries, to further promote the green development of textile auxiliary industries. Together, these measures can help mitigate irreversible damage to the environment and stimulate the birth of a more sustainable and responsible textile chemical industry.

3.3 Innovation Problems

To meet the demands of a high-quality lifestyle, numerous novel fibers have been developed. The development of new fibers has greatly enriched the textile industry and enhanced the functionality of textiles. Temperature-regulating fibers, for instance, possess the ability to adjust body surface temperature, providing individuals with optimal comfort in various environmental conditions. Cai et al. developed a novel fiber with selective spectral response by embedding zinc oxide nanoparticles into nanoporous polyethylene (Fig. 12a) [156]. Cai et al. utilized unique inorganic pigment nanoparticles to achieve coloration of infrared-transparent polyethylene textiles for radiative cooling (Fig. 12b) [157]. Cui et al. used a freeze-spinning technique to continuously fabricate silk fibroin solution into a thermally insulating fiber (Fig. 12c) [158]. Fei et al. designed a molecular solar thermal fabric using a microcapsule containing a deep-UV filter (Fig. 12d) [159]. Furthermore, smart fibers, integrated with sensors and electronic components, enable real-time monitoring and personalized health management, revolutionizing the way we track physiological parameters and environmental factors. Yang et al. reported a scalable fiber electronics that can simultaneously visualize and digitize the mechanical stimulus without external power supply (Fig. 12e) [160]. Zhang et al. fabricated an electronic yarn by continuously twisting P(VDF-TrFE) nanofibers on the surface of stretchable conductive yarn into Fermat-spiral structure (Fig. 12f) [161]. In addition, there are fibers that exploit the shape, arrangement, or periodicity of the microstructure to produce color effects. He et al. developed a saturated structurally colored polyester fabric based on silica photonic crystals [162]. Li et al. achieved rapid large-area preparation of photonic crystal structural color fabrics through external force shear-induced assembly technology [163]. This coloration arises not from the absorption of light at specific wavelengths by the material, but rather from light scattering, interference, or diffraction by the structure itself. The advancement of structural chromogenic fibers offers a fundamental resolution to the environmental challenges associated with conventional fabric dyeing and holds significant promise for practical applications.

Nevertheless, the progress in dyeing and finishing auxiliaries has not kept pace with the advancements in fiber technology. Due to the unique characteristics of these fibers, such as their composition and surface properties, the color management of these novel fibers often falls short of achieving the same level of richness as traditional fibers while ensuring functionality. Traditional dyeing techniques and colorants may not effectively penetrate or adhere to the surfaces of these fibers, resulting in less vibrant or uneven coloration. In addition, the functional properties integrated into the fibers, such as temperature regulation or moisture-wicking capabilities, can further complicate the dyeing process and hinder the achievement of desired colors. Furthermore, the formation of wrinkles and creases during mechanical manipulation is a common issue faced by certain novel fibers. This wrinkling phenomenon can occur due to their inherent structure or lack of sufficient elasticity, which makes them more prone to permanent deformation. As a consequence, the appearance and overall integrity of the fibers may be compromised, leading to dissatisfaction among consumers who seek visually appealing and well-maintained textiles. Hence, tackling these challenges necessitates the development of complementary novel auxiliaries. Once these technical hurdles are overcome, the textile industry can unlock the full potential of new fibers to meet the esthetic and functional needs of consumers.

4 Development and International Status of China's Textile Industries

Textile auxiliaries are substances designed to facilitate the production and enhance the performance of textiles. The current state of textile industries directly impacts the trajectory of textile auxiliaries. China, renowned as a prominent player in the global textile import and export market, holds significant influence over the development of its textile industries. Therefore, gaining knowledge about the present circumstances of China's textile industries becomes imperative.

4.1 Development Status of China's Textile Industries

Textile is an industry with high labor intensity and high dependence on foreign countries. In recent decades, China has witnessed a significant expansion in its textile production capacity, becoming the world's largest producer and exporter of textiles [164]. This rapid growth can be attributed to

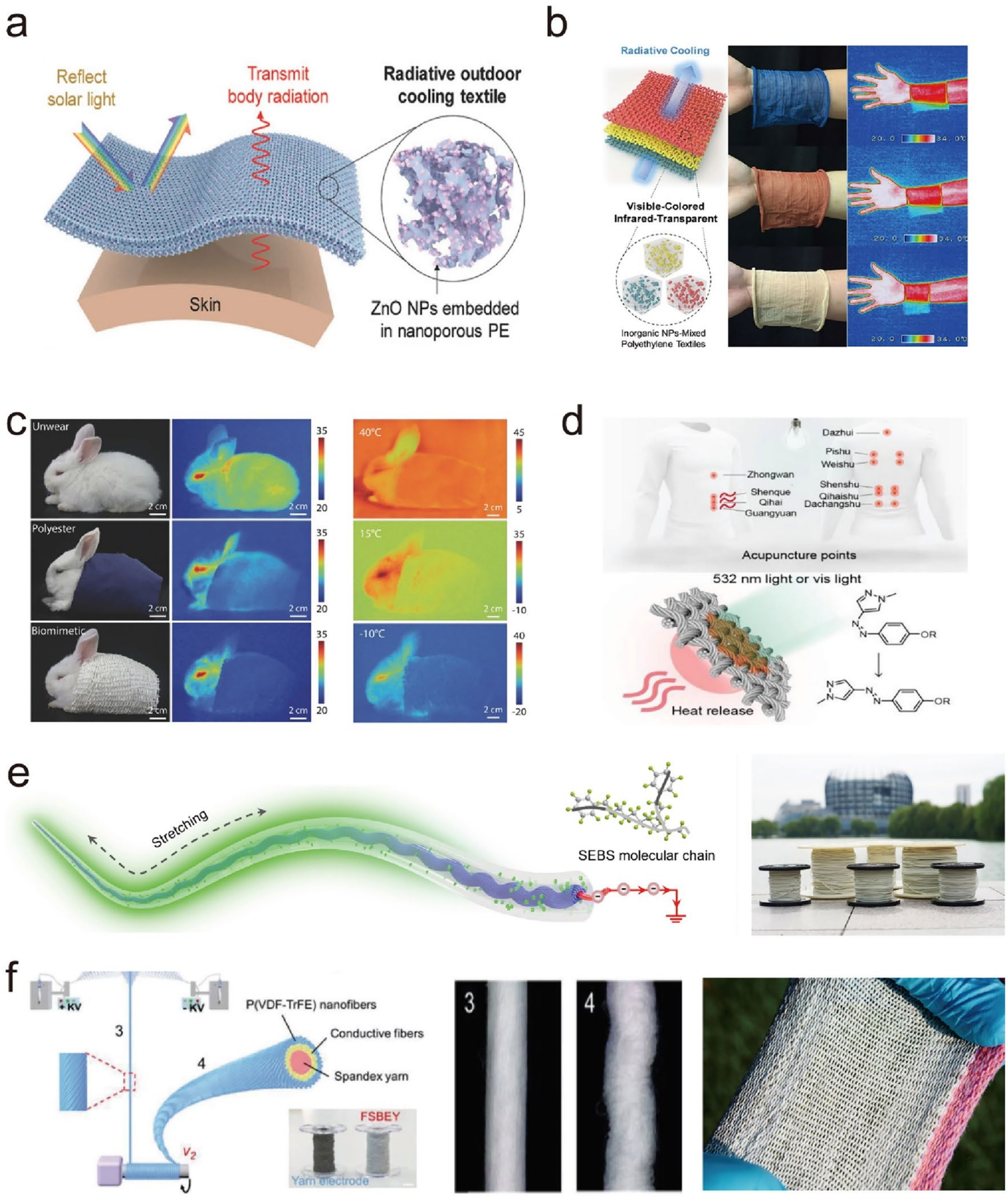


Fig. 12 **a** A novel fiber with selective spectral response for outdoor personal cooling, reproduced with permission from Ref. [156], Copyright 2023, *Wiley*, **b** infrared-transparent polyethylene textiles for radiative cooling, reproduced with permission from Ref. [157], Copyright 2019, *Elsevier*, **c** thermally insulating silk fibroin fiber, reproduced with permission from Ref. [158], Copyright 2018, *Wiley*, **d** efficient and robust molecular solar thermal fabric for personal thermal management, reproduced with permission from Ref. [159], Copyright 2023, *Wiley*, **e** the scalable fiber electronics that can simultaneously visualize and digitize the mechanical stimulus without external power supply, reproduced with permission from Ref. [160], Copyright 2021, *Wiley*, **f** an electronic yarn with Fermat-spiral structure, reproduced with permission from Ref. [161], Copyright 2021, *Wiley*

several factors, including abundant labor resources, technological advancements, and favorable government policies that have encouraged investment and innovation in the industry [165, 166]. China's textile industries encompass a wide range of segments, including fiber production, yarn spinning, fabric weaving, dyeing and printing, and garment manufacturing. A complete supply chain promotes efficient production and cost-effective operations, enabling Chinese manufacturers to compete on a global scale.

In 2022, the textile industry faced significant economic pressure due to sustained weak demand in domestic and international markets, domestic epidemics, geopolitical tensions, rising costs of logistics and transportation, as well as increasing prices of raw materials. According to data from the National Bureau of Statistics of China (Fig. 13a), in 2022, the value-added growth rate of the textile industry (TI), apparel manufacturing industry (AMI), and chemical fiber manufacturing industry (CFMI) above a designated scale was − 2.7%, − 1.9%, and 1.1%, respectively [167]. The output of national cotton was 5.977 million tons, representing increases of 4.3% compared to the previous year [168]. The production volumes of yarn, cloth, chemical fibers, and synthetic fibers were 27.191 million tons, 46.75 billion meters, 66.978

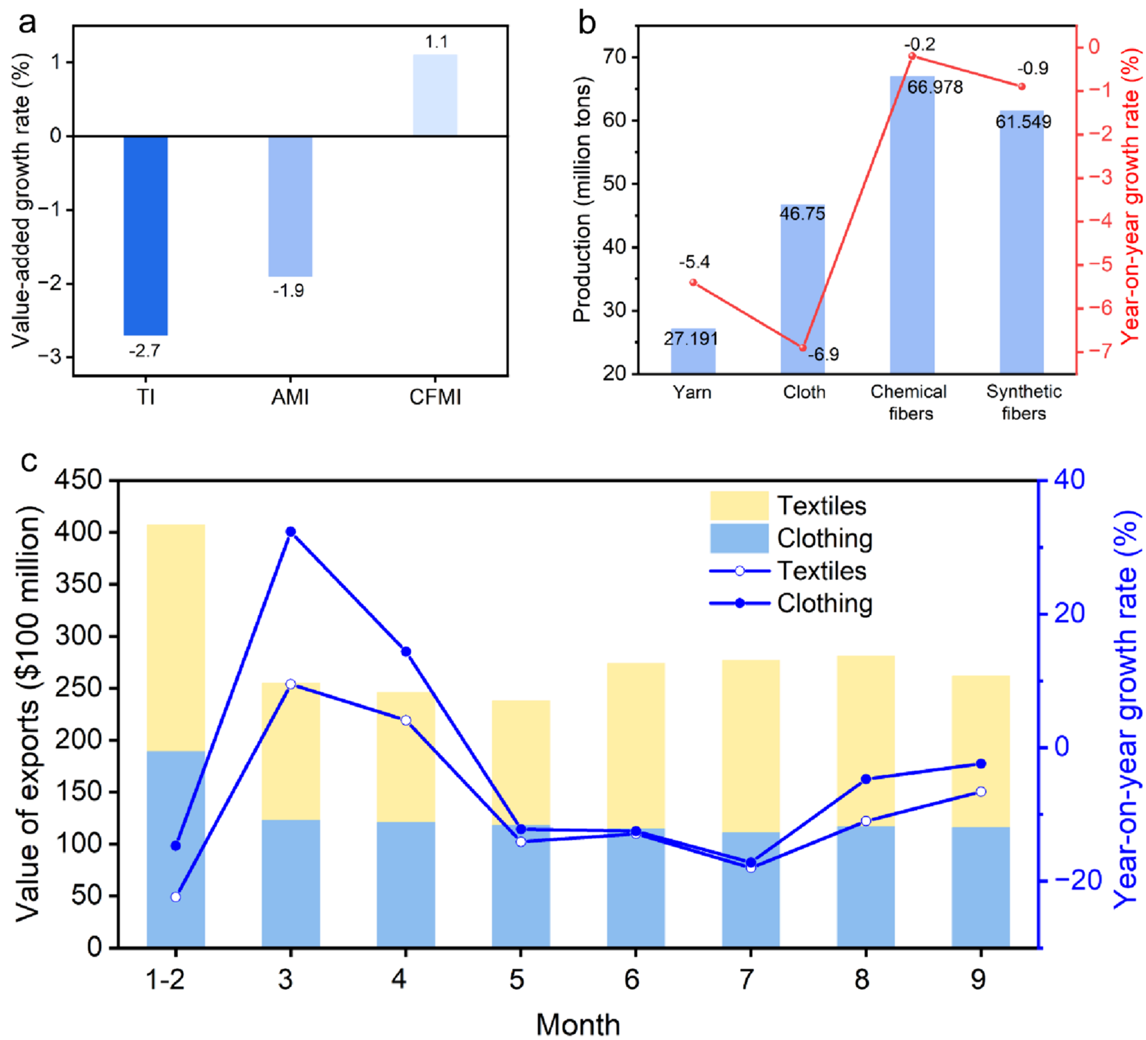


Fig. 13 **a** The value-added growth rate of the textile industry (TI), apparel manufacturing industry (AMI), and chemical fiber manufacturing industry (CFMI), **b** the production volumes of yarn, cloth, chemical fibers, and synthetic fibers, **c** China's textile and apparel export volumes in the first three quarters of 2023

million tons, and 61.549, respectively, down 5.4%, 6.9%, 0.2%, and 0.9% from 2021 (Fig. 13b) [167].

In the first three quarters of 2023, China's textile and apparel exports amounted to $223.15 billion, marking a 9.5% year-on-year decrease. Specifically, textile exports were valued at $101.92 billion, representing a 10.3% drop compared to the previous year, while apparel exports reached $121.23 billion, reflecting an 8.8% decline (Fig. 13c). In September, positive factors such as the gradual depletion of international brand inventories and the release of new order demands contributed to a recovery, leading China's textile and apparel exports to total $26.2 billion globally, a 4.8% decrease year-on-year, with the decline narrowing by 3.6 percentage points. This improvement signifies a noticeable warming trend compared to the preceding months. Within this period, textile exports amounted to $11.64 billion, marking a 2.4% decrease, while apparel exports were $14.56 billion, showing a 6.6% decrease compared to the same period last year.

4.2 Manufacturing Market Size of Clothing Textile Products

As shown in Fig. 14a, the number of professional clothing markets in China showed a trend of initial growth followed by decline from 2016 to 2022. The appearance of the turning point is mainly related to the outbreak of the epidemic. The corresponding year-on-year growth rates of the total turnover of the professional markets were 2.81%, 5.12%, 3.85%, − 1.08%, − 2.22%, 1.98%, and − 8.54%, respectively. There was a consecutive 2-year decline starting from 2019, and in 2021, the turnover of professional markets experienced renewed growth. However, in 2022, the turnover of professional markets once again showed a significant decline. In 2022, China's professional textile and apparel markets with an area of over 10,000 square meters witnessed a decline in market scale, operational area, number of market stalls, and number of retailers, decreasing by 6.56%, 3.92%, 4.34%, and 4.71%, respectively, compared to the previous year [169]. The significant decrease in overall scale can be attributed to two main factors. First, China's professional textile and apparel markets have long been characterized by excessive total capacity, severe homogenized competition, a prevalence of "zombie" markets, and polarization. Second, the compounding effects of the 3-year-long pandemic, the trend toward flattened distribution channels, and the emergence of the new e-commerce economy have collectively exerted substantial pressure and impact on traditional professional markets.

From a regional perspective, the quantity of professional markets in the eastern, central, and western regions accounts for 60.30%, 21.9%, and 17.8%, respectively (Fig. 14b). Among the 854 professional markets, the turnover in the

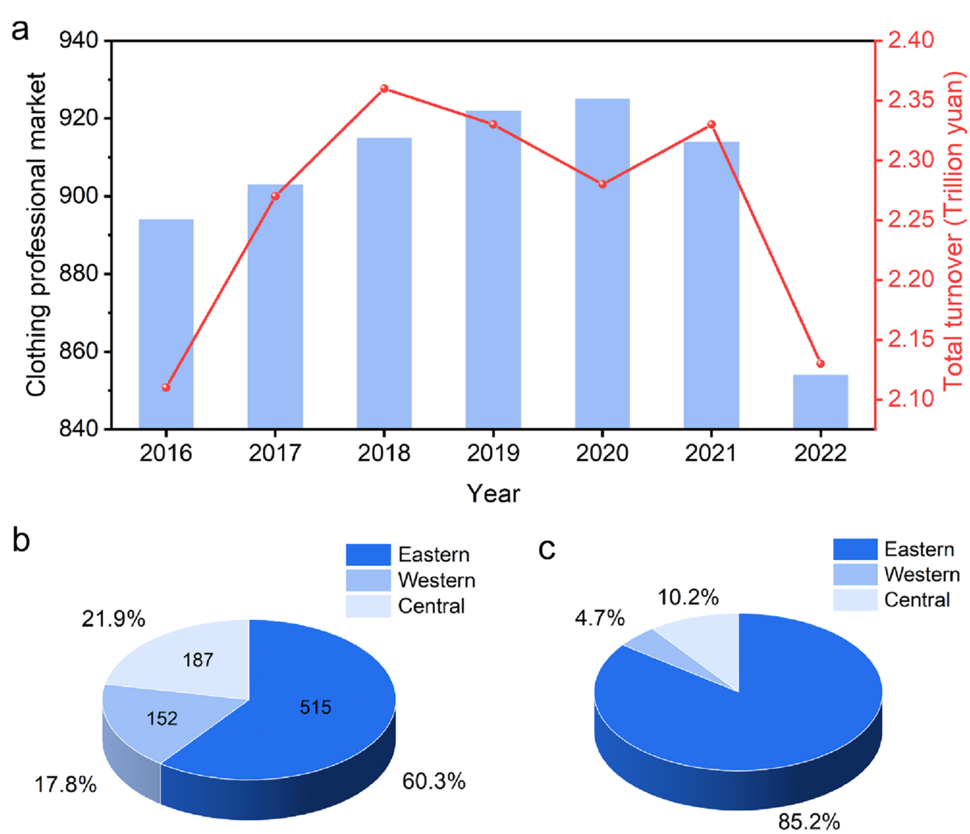


Fig. 14 **a** Number and turnover of clothing professional market from 2016 to 2022, **b** clothing professional market proportion of eastern, central, and western regions, **c** total turnover proportion of eastern, central, and western regions

eastern region was CNY 18,119.98 billion, accounting for 85.19% of the total turnover and decreasing by 6.94% year on year (Fig. 14c). The market turnover in the central region was CNY 2,160.69 billion, representing 10.16% of the total turnover and declining by 15.35% year on year. In the western region, the market turnover was CNY 989.26 billion, accounting for 4.65% of the total turnover and experiencing a 19.67% year-on-year decrease [169]. The decline in turnover of eastern region is lower than that in the central and western regions. This phenomenon can be attributed to the robust development of several leading market clusters, with turnovers reaching hundreds of billions or tens of billions of RMB in the eastern region. These leading market clusters have increasingly solidified their pivotal position in China's professional market industry.

In terms of product categories, clothing and raw materials/fabrics are the main commodities in China's professional textile and apparel markets, accounting for 70.49% of the total quantity and 69.21% of the turnover [169]. Data from 2022 indicate a year-on-year decrease of 17.54% in the turnover of professional markets specializing in clothing products, while the turnover of professional markets specializing in raw materials/fabrics rose by 0.13% [169]. This suggests that, against the backdrop of an overall industry downturn and increasing uncertainties, the impact on the raw materials/fabrics market is relatively minor, indicating a stronger ability to withstand risks.

With the continuous improvement of China's economic performance and the sustained enhancement of endogenous dynamics, as well as the ongoing effective implementation of initiatives such as the Belt and Road, the future development trend of China's textile and apparel market may present two aspects. First, the professional textile and apparel markets will continue to exhibit characteristics of reduced quantity, optimized structure, and enhanced levels of operation, with a constant aim to elevate the intensive development level of professional markets. Second, within the context of a new round of technological revolution, the circulation field of textile and apparel will actively embrace the direction of digitalization, networking, and intelligent development. It will strengthen the exploration and application of new platforms, new models, and new formats, continually constructing an industrial new ecology characterized by the integration of online and offline channels, coordinated supply chain management, and the integration of domestic and international trade, thereby achieving new positioning, new pathways, and new value for professional markets.

4.3 Manufacturing Market Size of Household Textile Products

As of 2020, household textile products accounted for 27% of the textile product structure, and it is expected that this proportion will remain unchanged until 2025. Household textiles belong to labor-intensive industries, with a wide range of sophisticated products and intricate manufacturing processes, thus exhibiting distinct industrial cluster characteristics. Currently, China has a total of 14 household textile industry clusters, mainly distributed in Jiangsu, Zhejiang, Shandong, Shanghai, Guangdong, and other regions. However, by 2022, the scale of production and sales in the household textile industry had contracted compared to the previous year. According to statistics, the operating income of household textile enterprises above a certain scale decreased by 4.11% year on year [170]. Despite the initial effects of industries' technological transformation, upgrading, and cost control, the operating costs and expenses of household textile enterprises above a certain scale decreased significantly over the year, with profits maintaining only a slight increase of 2.11% [170].

According to the export data, in 2022, China's exports of household textile products amounted to a total of $46.048 billion, representing a 3.85% year-on-year decrease [170]. Within this, the quantity of exports decreased by 8.42% year on year, while the unit price of the products increased by 4.99% year on year (Fig. 15a) [170]. Notably, the traditional markets of the USA, Europe, and Japan experienced significant declines, while the ASEAN market maintained relatively high levels of growth. In 2022, China's exports of bedding amounted to $13.547 billion, marking a 15.46% year-on-year decrease; towel exports amounted to $2.602 billion, showing a 4.93% year-on-year decrease; and fabric product exports amounted to $17.186 billion, with a slight increase of 1.02% year on year (Fig. 15b) [170].

From the perspective of domestic sales, it is evident that the annual domestic sales value of large-scale household textile enterprises remained relatively stable compared to the previous year, with some household textile enterprises and key industry clusters achieving modest growth in domestic sales value. Despite the significant challenges posed to household textile industry enterprises by the slow recovery of the consumer market, sudden increases in logistics pressure, and rising raw material costs, major players in the household textile industry are accelerating their pace of transformation and upgrading. They are actively expanding intelligent and branded transformation, emphasizing research and development as well as cost control, thereby further improving the industry's quality and efficiency levels. Against the backdrop of the nation's strong promotion of cultural confidence, household textile industry enterprises still have broad prospects for development within the prevailing trends of national sentiment, wellness, and sustainable development.

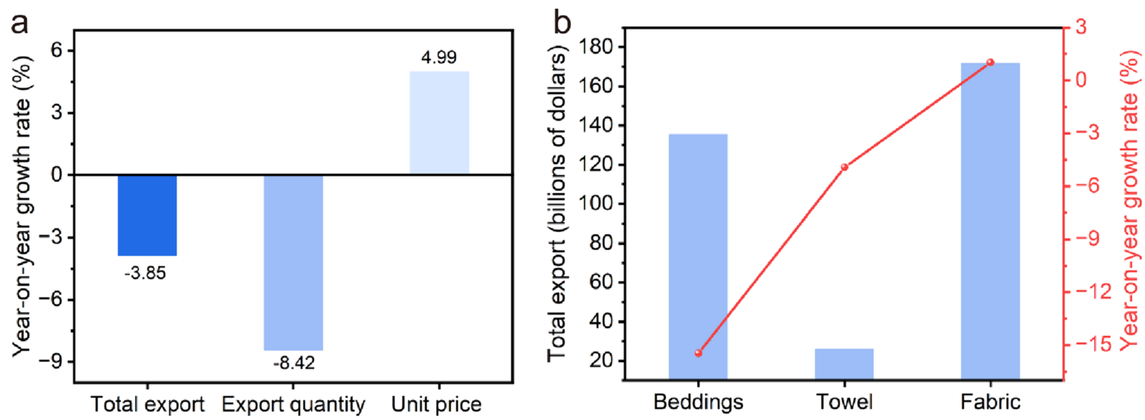


Fig. 15 **a** The year-on-year growth rate of total export, export quantity, and unit price in China's household textile products (2022), **b** the total export and year-on-year growth rate of beddings, towels, and fabric products

4.4 Manufacturing Market Size of Industrial Textile Products

Currently, China's industrial textile industries are still in the phase of recovery and adjustment following the extraordinary growth in 2020. During this phase, the industry continues to adhere to the concept of high-quality development while maintaining stability in the production of its main products. The capacity utilization rate of the industrial textile industry has shown a trend of initial decline followed by a subsequent increase. According to association statistics, in 2022, China's industrial textile industries processed a total of 19.61 million tons of fibers, representing a 1.1% year-on-year increase [171]. As shown in Fig. 16a, the prosperity index for the industrial textile industry in 2022 was 57.3, exhibiting a significant decrease compared to the same period in 2021 (73.8), but still remaining above the threshold line.

The operating income of large-scale enterprises in the industrial textile industry remained largely unchanged compared to the same period in 2021, but the total profit decreased by 8.9% year on year, and the operating profit rate was 4.7%, reaching a low point in recent years (Fig. 16a) [171]. The main reasons for the decline in industry profitability include repeated outbreaks of the pandemic, fluctuation in raw material costs, and excessive competition. In terms of product categories, the operating income and total profits of large-scale enterprises in the non-woven fabric, rope and cable, and textile belt and curtain industries all showed a declining trend. Benefiting from the rapid development of the "camping economy," the tent and canvas industry maintained a strong growth momentum, with the operating income of large-scale enterprises increasing by 0.2% year on year, and the total profit increasing by an impressive 16.6% (Fig. 16b) [171]. Both the gross profit margin and the operating profit margin reached 17.2% and 6.5%, respectively, which are the highest in the industry [171]. Driven by new infrastructure construction and air pollution control, other industrial textiles such as geotextiles and filtration textiles also showed signs of stabilization and improvement.

In terms of exports, the export value of China's industrial textile industries in 2022 was $44.15 billion, a decrease of 15.9% compared to the previous year, but still maintaining steady growth compared to prepandemic levels [171]. Industrial coated fabrics and felts/tents are the top two export products in the industry, with export values reaching $4.99 billion and $4.43 billion, respectively, in 2022, representing a year-on-year growth of 16.7% and 0.9%, respectively (Fig. 16c, d) [171]. The export prices of the industry's main products have also increased to varying degrees.

Looking at the import situation, China's demand for major products (such as non-woven fabrics, industrial fiberglass products, industrial coated fabrics, and disposable sanitary products) has generally weakened. In 2022, the import value of China's industrial textile industries was $61.3 billion, a decrease of 15.9% compared to the previous year [171]. It is worth noting that there has been a persistent trade deficit in the import and export of structural strengthening textiles, indicating an urgent need for imports. The import value of structural strengthening textiles reached $640 million, representing an 8.1% year-on-year growth [171].

Since the outbreak of the epidemic, China's industrial textile industry has experienced stages of rapid growth, subsequent adjustments, and gradual stabilization. During this period, the industry has seen accelerated restructuring, with simultaneous integration and exit. It is expected that by 2023, the production and sales of China's industrial textile industries will recover to a moderate growth rate of around 5%, with improved profitability. The focus of industries' fixed asset investment will shift toward equipment upgrades, intelligent transformation, and green manufacturing, while the industry's exports are expected to experience a revival.

5 Outlook

Textile research is of prime importance to the society, and using auxiliaries to assist in enhancing production efficiency, improving product quality, and meeting market demands may help alleviate environmental stress worldwide. As shown in Fig. 17, the fundamental and pivotal challenges such as the synthesis of textile auxiliaries and the mechanisms of interaction between auxiliaries and fibers have been overcome in the past period. At present, the research of textile auxiliaries focuses on functional enhancement and sustainability improvement. Although textile auxiliaries have been developed for almost a century, the ever-increasing market demands, continual advancements in textile technology, and dynamic shifts in development paradigms collectively propel the iterative upgrading of textile auxiliaries. Based on the current industry situation, three innovative directions of textile auxiliaries are presented below.

5.1 Green Textile Auxiliaries

The textile industry has been facing increasing pressure to adopt sustainable practices and reduce its environmental impact. As a result, the development of green auxiliaries has become a promising area for innovation and growth in the field of textile auxiliaries. Green auxiliaries are those that are designed with sustainability in mind, utilizing environmentally friendly materials and processes. First of all, green auxiliaries minimize the release of harmful chemicals and pollutants into the environment. They are biodegradable and do not contribute to soil and water pollution, leading to a more sustainable and eco-friendly textile industry. Next, the use of green auxiliaries reduces the exposure of workers to harmful chemicals and toxins, safeguarding their health and safety. In addition, they enhance the quality of the final product, ensuring that it is safe for consumers to use.

However, green auxiliaries may have limited compatibility with some textile fibers or dyes, resulting in reduced performance. Researchers can focus on developing green auxiliaries that are compatible with a wider range of textile materials while maintaining their eco-friendliness. In addition, compared with traditional auxiliaries, low performance or efficiency is still the bottleneck of green auxiliaries. The development of green auxiliaries that match the effectiveness of traditional ones can be achieved through a focus on novel material properties and advanced manufacturing processes. Furthermore, there is a lack of standardization in the labeling and certification of green auxiliaries, making it difficult for manufacturers to identify environmentally friendly products. The development of standardized certifications and labeling systems can help promote the use of green auxiliaries and simplify the selection process for manufacturers.

5.2 Functional Auxiliaries for Industrial Fibers and Outdoor Sports Clothing

There is a growing demand for high-performance functional textiles in industries such as automotive, aerospace, construction, and sports. Besides, the increasing demand for healthy lifestyles and outdoor recreation has stimulated the continuous expansion of the global market for sports and leisure clothing. Especially in the context of a slight downturn in the overall textile industry, the market for sports and leisure clothing has exhibited counter-cyclical growth in 2022.

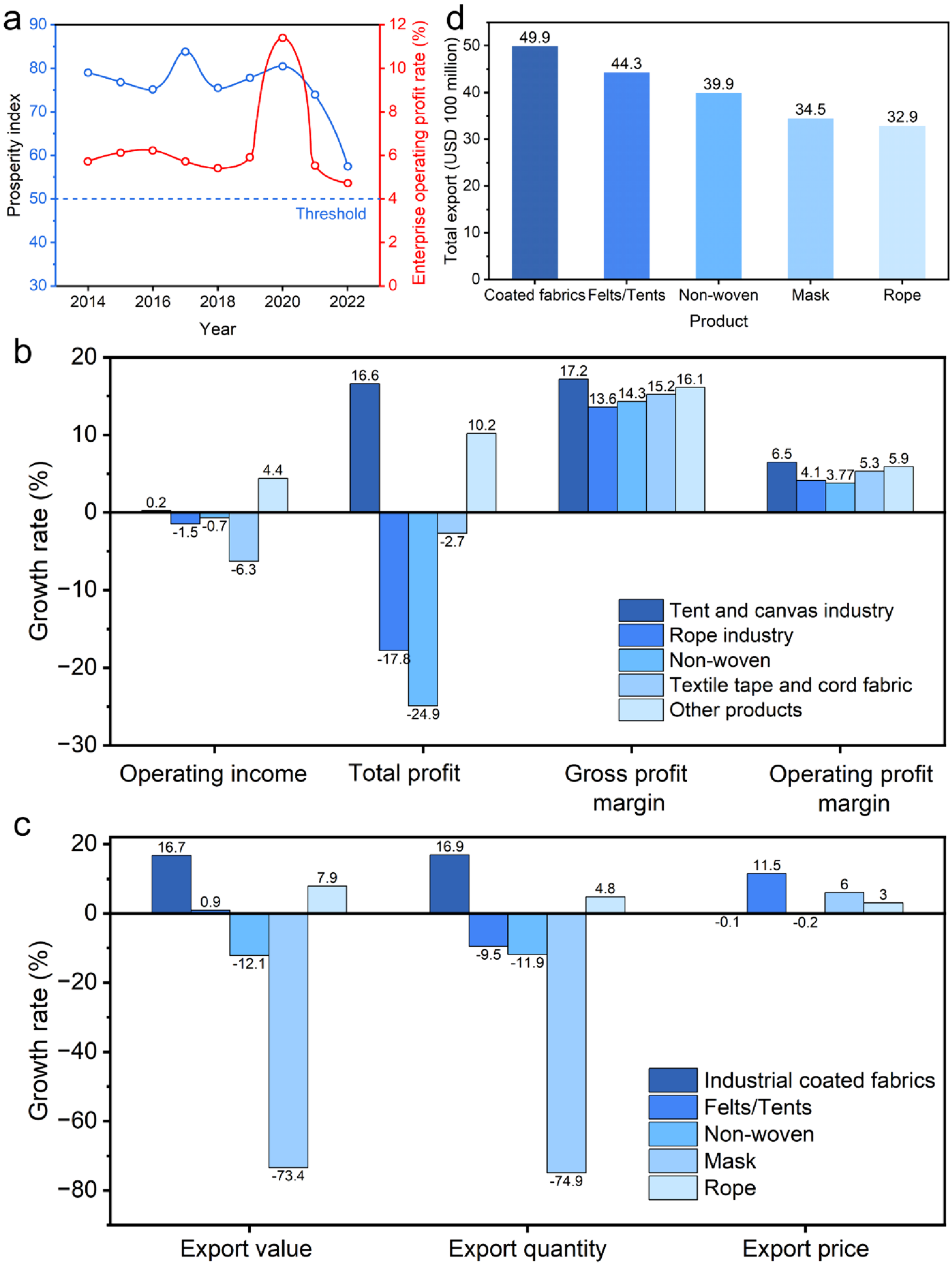
Functional auxiliaries are specialized additives used in the processing of industrial fibers and the production of outdoor sports clothing. They impart desirable properties such as moisture management, temperature management, UV protection, antibacterial effects, flame retardancy, and mechanical strength enhancement. Improving the overall quality and durability of functional textiles is crucial to meet the growing demands for high-performance products in various industries. For example, in the automotive industry, there is a need for durable and flame-retardant textiles in car interiors. In the sports industry, functional auxiliaries that enhance moisture management and temperature regulation are in high demand to improve the performance and comfort of athletes.

While functional auxiliaries enhance various properties of industrial fibers and outdoor sports clothing, certain auxiliaries may compromise the mechanical strength and durability of these textiles. One example of functional auxiliaries that can compromise the mechanical strength and durability of textiles is UV protection auxiliaries. These auxiliaries can cause fiber degradation over time, reducing the lifespan of the textile and compromising its overall performance. To address this issue, researchers can employ innovative approaches such as nanotechnology, which involves the manipulation of materials at the molecular level to enhance their properties.

5.3 Auxiliaries for Digital Printing

The advent of digital printing technologies has revolutionized the textile industry, offering numerous advantages such as reduced water consumption, improved color accuracy, and increased design flexibility. However, the successful implementation of digital printing heavily relies on the effective utilization of auxiliaries.

First, auxiliaries can be tailored to improve the color fastness properties of digitally printed textiles, ensuring long-lasting and vibrant colors even after multiple washes or exposure to light. They assist in optimizing the fixation of colorants onto the fabric and minimizing dye migration issues. Second, auxiliaries designed


a
Prosperity index
Enterprise operating profit rate (%)
Threshold
Year
d
Total export (USD 100 million)
49.9
44.3
39.9
34.5
32.9
Coated fabrics
Felts/Tents
Non-woven
Mask
Rope
Product
b
Growth rate (%)
Tent and canvas industry
Rope industry
Non-woven
Textile tape and cord fabric
Other products
Operating income
Total profit
Gross profit margin
Operating profit margin
c
Industrial coated fabrics
Felts/Tents
Non-woven
Mask
Rope
Export value
Export quantity
Export price

◀**Fig. 16** **a** The prosperity index and enterprise operating profit rate of industrial textile industries, **b** growth rate of the main economic indicators of China's industrial textile industries in 2022, **c**-**d** the export of the main products of China's industrial textile industries in 2022

specifically for digital printing systems can enhance ink dispersion, prevent nozzle clogging, and improve the adherence of ink to the fabric surface. This leads to sharper and more precise prints with excellent color saturation and image resolution. Third, auxiliaries aid in preparing fabrics for digital printing processes by improving the ink receptivity and increasing the uniformity of the substrate. They can help in enhancing the effectiveness of color fixation and reducing ink bleeding.

Current digital printing processes often encounter challenges in reproducing certain complex colors due to the limited color gamut of available inks and colorants. Development of innovative auxiliaries that can enhance color reproduction and expand the achievable color range is crucial. Moreover, ensuring excellent wash- and lightfastness properties of digitally printed textiles remains a challenge. Researchers can focus on developing auxiliaries that enhance color fixation and increase the durability of prints under various environmental conditions. Reducing nozzle clogging is also an urgent problem. Specialized cleaning agents, antistatic agents, dispersing agents, and viscosity modifiers need to be designed for digital printing to lowering the risk of blockages and

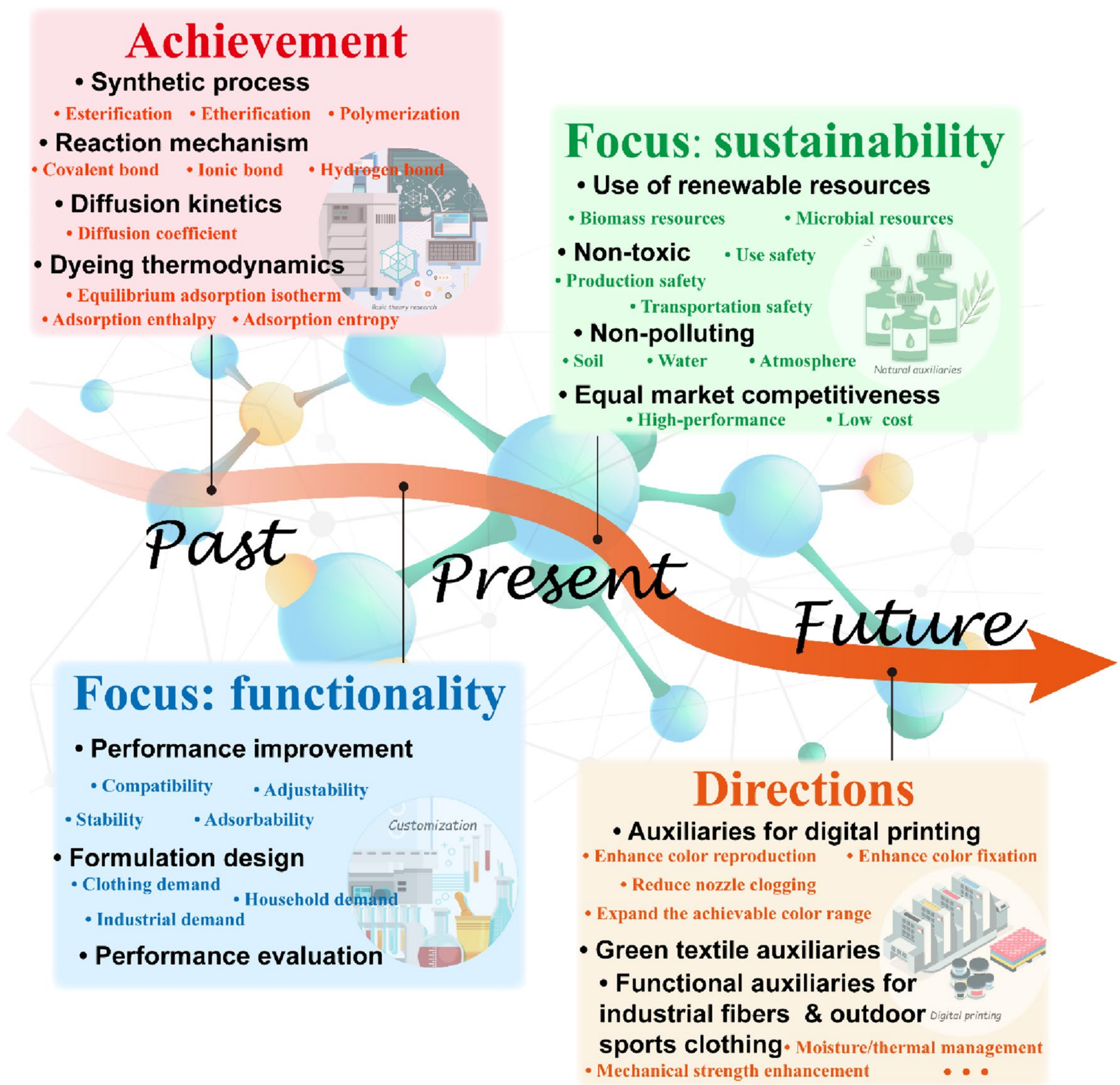


Fig. 17 Roadmap for the development of textile auxiliaries: past, present, and future

preserves print quality. Last but not the least, the textile industry is increasingly concerned about the environmental impact of printing processes. Future development of digital printing auxiliaries should emphasize the use of eco-friendly and biodegradable materials, as well as optimizing the efficiency of auxiliaries to minimize waste generation.

At present, the scale of China's textile industries has exceeded 50% of the world, chemical fiber production accounts for 70% of the world, and trade accounts for one-third of the world. China's textile industries have become a core force supporting the smooth operation of the world's textile industry system and an important industrial platform for promoting global economic and cultural cooperation and governance. In the post-epidemic era, with the dramatic changes in the global textile consumer market and the layout of the global textile industry chain, what is the future of China's dyeing and printing processing and textile auxiliary industries? How should China's textile auxiliary manufacturers cope with the current predicament? Only by insisting on scientific and technological innovation and improving the ability of independent innovation can we promote the sustainable development of the industry with high quality. Only by maintaining the core competitiveness of enterprises can they survive in the current rapidly changing market environment.

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Data availability statement The data used in this study will be made available upon request to the corresponding authors.

Declarations

Conflict of Interest The authors declare no conflict of interest.

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