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Cationic Surfactants in Textile Processing

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Abstract: Textile wet processing involves essential steps such as pretreatment, dyeing, printing, and finishing to improve the quality and functionality of textile materials. Surfactants, with their amphiphilic nature, play a pivotal role in these processes. This review highlights cationic surfactants' unique properties and wide-ranging applications in textile wet processing. It examines their types, mechanisms of action, and specific uses in enhancing fiber performance. Additionally, the discussion includes their advantages, limitations, and recent technological advancements, offering insights into how these compounds contribute to improved process efficiency and product quality. The environmental implications of cationic surfactants are also addressed, emphasizing the importance of sustainable practices and eco-friendly innovations in the textile industry. Cationic surfactants impart functionalities such as antimicrobial properties, moisture management, and self-cleaning capabilities. Structural correlation in terms of the function and the application performance of the quaternary ammonium compound-based products is elucidated. The economic implications of cationic surfactant usage in textile processing are significant. The economic implication can be derived based on the benefits of the efficient application, which can lead to reduced processing times, lower energy consumption, and improved product quality, all of which contribute to cost-effective manufacturing. Finally, the review explores future trends and potential research directions to balance industrial utility with environmental responsibility.

Keywords: Detergent Developments, Surface Tension, Surfactant Formulation, Sustainable Processing, Textile Pretreatment

Abbreviations:
DAA: Diallyl Amine
BAC: Benzalkonium Chloride
QACs: Quaternary Ammonium Compounds
DDAC: Dodecyl Dimethyl Ammonium Chloride
CTAB: Cetyl Trimethy Lammonium Bromide

I. INTRODUCTION

Cationic surfactants are the most vital classes of chemical compounds discovered to date, drastically altering the way textile processing is done. Molecules with a positively charged hydrophilic head and a hydrophobic tail are important in fabric preparation, finishing treatments, and essential functions in textile manufacturing processes [1]. Because of its unique molecular structure, it allows compatibility with others of the same type, especially the non-ionic and amphoteric variants.

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In textile processing, the journey from raw fiber to finished fabric entails multiple critical operations such as desizing, scouring, bleaching, dyeing, printing, and functional finish application. Cationic surfactants played a crucial role in this chain of processing, especially for fabric finishing, where they acted as the major active component in various treatment formulations.

Their efficacy was not only because of their surface activity but also their molecular structure and specific interactions with fibre surfaces [2].

The strategic significance of cationic surfactants in textile applications is in their ability to facilitate the controlled deposition and attachment of long-chain fatty compounds onto fiber surfaces [3]. By introducing solubilizing groups to create water-dispersible compounds, molecular modification allows for precise application from aqueous solutions while enhancing substantivity the natural affinity between the finishing agent and the fiber [4].

Technological advancement and market demands have been driving the evolution of cationic surfactants in textile processing. Traditionally, these applications were limited to fabric softening and antistatic properties, but modern developments have greatly enhanced their utility. The compounds are used for critical functions such as antimicrobial finishing, wrinkle resistance, water repellence, and even smart textile applications. Cationic surfactants have versatile applications since they are known to form stable complexes with the surface of fibres carrying negative charges during processing conditions, such as cotton, wool, and synthetic fibres. One of the most significant advantages of cationic surfactants in textile processing is their ability to modify surface properties without compromising the bulk characteristics of the fiber [5]. This selective surface modification allows for the development of textiles with enhanced functionality while maintaining their fundamental physical and mechanical properties. Furthermore, the strong electrostatic interactions between cationic surfactants and fiber surfaces often result in treatments with improved durability, addressing a long-standing challenge in textile finishing. Recent developments in cationic surfactant research have focused on addressing environmental concerns and improving performance characteristics. Researchers are increasingly exploring biodegradable alternatives to traditional quaternary ammonium compounds, aiming to minimize environmental impact while maintaining or enhancing functional properties. These efforts are particularly crucial given the growing awareness of environmental sustainability in textile manufacturing and the stringent regulations governing chemical discharge from textile processing facilities.

The economic implications of cationic surfactant usage in textile processing are significant. Their efficient application can lead to reduced processing times, lower energy consumption, and improved product quality, all of which contribute to cost-effective manufacturing. Moreover, developing multifunctional cationic surfactants has enabled the combination of multiple finishing treatments in single-step processes, further streamlining production workflows [6]. This review examines the significant role of cationic surfactants in textile processing and manufacturing, exploring their applications, mechanisms of action, and environmental considerations. By synthesizing current research and industrial practices, we aim to provide a comprehensive understanding of these crucial chemical compounds in textile production, addressing both traditional applications and emerging trends in the field [7].

The use of cationic surfactants in textile processing also extends to enhancing fabric softness, improving dye uptake, and providing antimicrobial properties to finished textiles. These advantages not only improve the overall quality of the final product but also contribute to increased consumer satisfaction and potentially higher market demand. Additionally, ongoing research in cationic surfactants explores their potential in developing smart textiles with self-cleaning or moisture-wicking properties, opening up new avenues for innovation in the textile industry. The versatility of cationic surfactants in textile processing extends beyond their primary functions, as they also play a crucial role in enhancing the performance of other textile chemicals and processes [8].

Their ability to modify fibres' surface properties can improve subsequent treatments' efficiency, such as dyeing, printing, and finishing. Furthermore, developing novel cationic surfactants with improved biodegradability and reduced environmental impact is an active area of research, addressing growing concerns about sustainability in the textile industry [9]. The review also discusses future perspectives and challenges in developing and applying cationic surfactants, particularly focusing on sustainability, performance optimization, and novel functionalities in smart textile applications. The review further delves into the potential for cationic surfactants to enhance the sustainability of textile manufacturing processes, exploring their role in reducing water consumption and minimizing the use of harmful chemicals [10]. Additionally, it examines the latest advancements in smart textile applications, where cationic surfactants play a crucial role in imparting functionalities such as antimicrobial properties, moisture management, and self-cleaning capabilities. The discussion also extends to the ongoing research efforts to develop bio-based and biodegradable cationic surfactants, addressing the growing demand for eco-friendly alternatives in the textile industry [11].

II. CLASSIFICATION OF SURFACTANTS

Surfactants are typically categorised based on their ionic behaviour in aqueous solutions and categorised into four main groups.

A. Anionic Surfactants

These carry a negative charge and find widespread application in laundry detergents, dishwashing liquids, household cleaning products, and personal care items. Common anionic surfactants include linear alkylbenzene sulfonate, alcohol ethoxy sulfates, alkyl sulfates, and traditional soaps [12].

B. Non-Ionic Surfactants

Characterized by their low foaming properties, these uncharged molecules are particularly suited for laundry formulations, automatic dishwasher detergents, and rinse aids. Alcohol ethoxylates represent the most commonly used non-ionic surfactants.

C. Cationic Surfactants

These positively charged compounds are essential ingredients in fabric softeners and fabric-conditioning laundry products. They also serve as disinfecting and sanitizing agents in various household cleaners. Quaternary ammonium compounds constitute the primary class of cationic surfactants.

D. Amphoteric Surfactants

These versatile molecules possess both positive and negative charges, making them valuable for personal cleansing and household cleaning formulations due to their gentle nature, excellent foam generation, and stability. The main amphoteric surfactants are imidazolines and betaines [13].

III. CATIONIC SURFACTANTS

Cationic surfactants are characterized by their positively charged hydrophilic groups, typically involving a nitrogen atom in their structure (e.g., quaternary ammonium compounds). These surfactants can be classified as

A. Quaternary Ammonium Compounds (QACs)

These are the most common type, known for their antimicrobial properties and excellent wetting and softening effects. Examples include cetyltrimethylammonium bromide (CTAB) and benzalkonium chloride (BAC) [14].

B. Imidazolinium Compounds

These are known for their high thermal stability and good compatibility with other chemicals. They are often used in textile printing and finishing [15].

i. The mechanism of action of cationic surfactants primarily involves their adsorption on negatively charged fabric surfaces, such as *cotton* and wool, which are negatively charged in the presence of water or ionic solutions. The positive charge of the surfactant enables strong electrostatic interactions with the fabric, enhancing fabric wetting, improving dye uptake, and providing antistatic properties.

A. Quaternary Ammonium Compounds

ii. *Benzalkonium Chloride (BAC),* a quaternary ammonium compound, is widely used as a disinfectant, antiseptic, preservative, and surfactant in various industries, including textiles, pharmaceuticals, cosmetics, and water treatment. The production of BAC involves the quaternization of alkyl dimethyl amines with benzyl chloride [16].

The manufacturing process is based on the quaternization reaction:

$$R{-}N(CH_3)_2 + C_6H_5CH_2Cl \rightarrow [R{-}N^{+}(CH_3)_2{-}CH_2C_6H_5]\ Cl^-$$

Where, **R represents** the alkyl chain, usually derived from C_{12} (dodecyl), C_{14} (myristic), or C_{16} (cetyl) groups.

The synthesis of benzalkonium chloride (BAC) is based on the quaternization reaction between an alkyl dimethyl amine and benzyl chloride.

The reaction follows a nucleophilic substitution mechanism (SN2), where the lone pair of electrons on the nitrogen of the alkyl dimethyl amine ($R-N(CH_3)_2$) attacks the electrophilic carbon of benzyl chloride ($C_6H_5CH_2Cl$). This results in the displacement of the chloride ion (Cl^-) and the formation of a quaternary ammonium salt, benzalkonium chloride ($[R-N^+(CH_3)_2-CH_2C_6H_5]Cl^-$). The reaction is exothermic and occurs under controlled conditions, typically at temperatures between 30°C and 80°C to prevent side reactions such as over-alkylation or degradation of the reactants. Excess benzyl chloride ensures complete quaternization, while the reaction medium (water or an organic solvent) helps optimise yield and purity. The reaction is carefully monitored to avoid unwanted byproducts and ensure high conversion efficiency [17].

iii. *Diallyl Dimethyl Ammonium Chloride (DADMAC)* is synthesised through a quaternization reaction between diallyl amine (DAA) and methyl chloride (CH_3Cl). The process begins with the reaction of diallyl amine, which contains two allyl groups, with methyl chloride, forming a quaternary ammonium salt. This reaction is exothermic and typically carried out at a controlled temperature of 50–80°C in a solvent such as water, methanol, or ethanol. The methyl chloride alkylates the nitrogen in diallyl amine, converting it into DADMAC. After the reaction, the mixture undergoes neutralization with a diluted acid or base to adjust the pH, followed by purification through filtration or phase separation to remove unreacted materials and impurities. [18]. The final product is then concentrated to obtain a 40–65% aqueous solution or further processed by spray drying to yield a solid form. Key considerations include controlling the reaction temperature and pH to prevent unwanted side reactions, ensuring purity by eliminating residual amines and chloride impurities and storing the product in sealed containers to maintain stability. DADMAC is widely used in polymerization to produce Poly-DADMAC, a coagulant essential for water treatment, as well as in the textile, paper, and personal care industries [19].

iv. *Distearyl dimethyl ammonium Chloride* Distearyl dimethyl ammonium chloride (DSDMAC) is the predominant cationic surfactant for textile conditioning and aftertreatment processes. This compound features two extended alkyl substituents derived from hydrogenated tallow, making it the most significant cationic detergent in the industry [20]. Its long-chain alkyl components primarily consist of a mixture of C16 and C18 homologues. Regarding the anionic counterpart, European manufacturers generally prefer *chloride*, while methyl sulfates and chlorides are utilized considerably in America.

The synthesis of DSDMAC typically follows one of two main production routes: [21].

v. *From fatty acid:* This method begins with converting fatty acids to nitriles. These nitriles undergo hydrogenation to form secondary amines, which are subsequently transformed into tertiary amines using either formaldehyde and formic acid or methyl chloride. In the final step, these tertiary amines react with methyl chloride to produce the quaternary ammonium compound [22].

Step 1: Amide Formation

$$R-COOH + NH_3 \rightleftharpoons R-CONH_2 + H_2O$$

Step 2: Dehydration to Nitrile

$$R-CONH_2 \xrightarrow{\Delta H} R-CN + H_2O \text{ (}\Delta H\text{ represents heat)}$$

Step 3: Nitrile Reduction to Amine

$$2\,R-CN + 4\,H_2 \rightarrow R-CH_2-NH-CH_2-R + NH_3$$

Step 4: Amine Reaction with Formaldehyde/Formic Acid or Methyl Chloride

$$R-CH_2-NH-CH_2-R + HCOOH + CH_2O \rightarrow R'-CH_2-N(CH_3)-CH_2-R + CO_2 + H_2O$$

Where R = R'-CH₂- (and R' represents the "hydrogenated tallow alkyl" group)

Step 5: Quaternization with Methyl Chloride

$$R-CH_2-N(CH_3)_2-CH_2-R + CH_3Cl \rightarrow [R-CH_2-N(CH_3)_3-CH_2-R]Cl$$

vi. *From fatty alcohols:* This synthesis pathway begins with fatty alcohols as the starting material, which are converted into secondary amines. These secondary amines undergo methylation with methyl chloride. The process continues by adding another mole of methyl chloride to generate the quaternary ammonium compound. Dimethyl sulfate is used instead of methyl chloride in the final methylation step to produce a variant with methyl sulfate as the counter-ion.

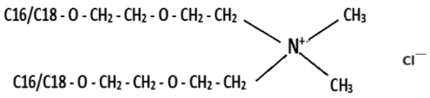
Step 1: Formation of Secondary Amine

$$2R'-CH_2OH + NH_3 \xrightarrow{Cat.} R_2NH + 2H_2O$$

Step 2: Formation of Quaternary ammonium salt

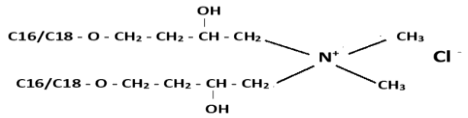
$$R_2NH + 2CH_3Cl \longrightarrow R_2N^+(CH_3)_2Cl^- + HCl$$

The properties of quaternary ammonium compounds are primarily determined by three key structural factors: the substituent structure (particularly chain length), degree of saturation, and number of oxygen atoms. Modifications to the saturated alkyl chain significantly impact both softening performance and the pourability of formulations. A notable example of this structure-property relationship is seen in the physical state difference between two similar compounds: distearyl dimethyl ammonium chloride exists as a solid, while ditallow-alkyl-hydroxypropyl methyl ammonium chloride is liquid at room temperature [22]. Incorporating hydroxy groups within quaternary ammonium compound substituents or unsaturated fatty alkyl chains enhances solubility, improving finished properties. Product finishing can also be facilitated by using coco alkyl substituents with shorter carbon chains. Similarly, adding ether groups, as found in bis (fatty alkyl diethoxy) dimethyl ammonium chloride, produces comparable effects on solubility and handling properties. Polyethoxylated ammonium salts demonstrate a clear relationship between ethoxy group content and softening performance. Generally, as the number of ethoxy groups increases, the softening effectiveness decreases [23].



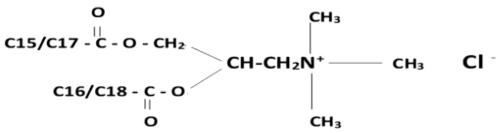
[Fig.1: bis (Tallow-Alkyl Diethoxy) Dimethyl Ammonium Chloride]

By converting products of 1-chloro-2-hydroxy- 3-alkoxy propane with secondary amines, e.g., bis (2- hydroxy-3-tallow-alkoxypropyl) dimethyl ammonium chloride, we get better properties with regards to colour and odour. The advantage of these ester ammonium salts is due to the formation of aqueous dispersions during their production. Also, these dispersions do not contain inflammable alcohol and can be immediately used after adequate dilution [24].



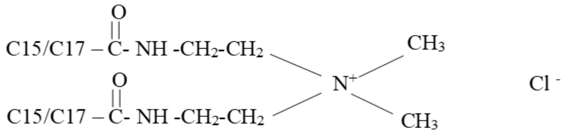
[Fig.2: bis(2-Hydroxy-3-Taliow-Alkoxypropyl) Dimethyl Ammonium Chloride]

Other diesters are the conversion products of dihydroxy propyl trimethylamine with fatty acids, e.g., 1,2-bis (tallow-alkyl carboxy) propyl trimethyl ammonium chloride. When compared to the corresponding monoester ammonium salts, these kind of diester ammonium salts show a greater textile-softening effect [25].



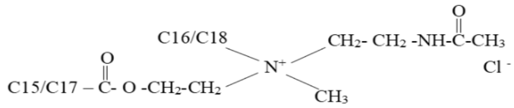
[Fig.3: 1,2 Bis (Tallow-Alkyl Carboxy) Propyl Trimethyl Ammonium Chloride]

Some other cationic that can particularly increase fabric softness along with their detergence properties are bis (2-alkyl amido ethyl) dimethyl ammonium salts, e.g., bis(tallow-aminoethyl) dimethyl ammonium chloride. Ethoxy groups can be incorporated between the amide and ethylene groups [26].



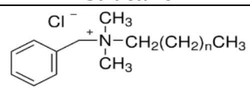
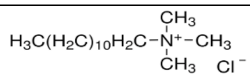
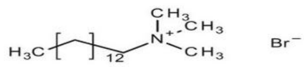
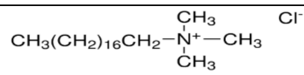
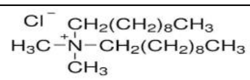
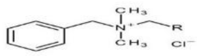
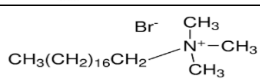
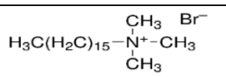
[Fig.4: bis (Tallow-Amido Ethyl) Dimethyl Ammonium Chloride]

Certain quaternary ammonium compounds incorporate both the ester and amide functional groups as substituents on the nitrogen atom to achieve superior finishing properties [27]. These compounds feature a distinctive structural arrangement: one long alkyl chain connects directly to the nitrogen atom, while the other attaches through an ester linkage (connecting ethyl or propyl groups) to a fatty acid substituent. A representative example of this structural class is tallow-alkyl (tallow-alkyl carboxyethyl)-acetamido ethyl ammonium chloride [28].



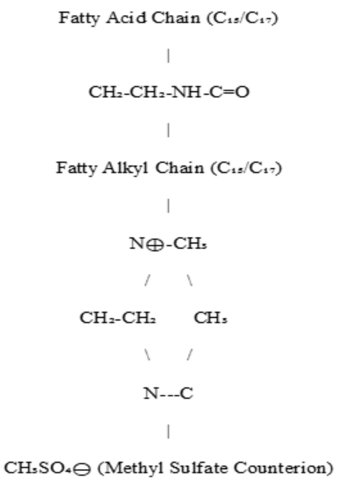
[Fig.5: Tallow-Alkyl- (Tallow-Alkyl Carboxyethyl) Acetamido Ethyl Ammonium Chloride]

Table-I: Properties and Functions of Quaternary Ammonium Compounds in Textile Applications

Quaternary Compounds	Application	Function	Structure
Benzalkonium chloride (BAC)	Antimicrobial treatment, dyeing process, weight reduction of polyester	Provides antibacterial and antifungal properties to textiles during antimicrobial treatment	
Dodecyl trimethyl ammonium chloride	Dyeing and printing processes	Serves as a levelling agent to ensure even dye distribution.	
Tetradecyltrimethylammonium bromide	Fabric conditioning	Improves softness and smoothness of fabric.	
Stearyl trimethyl ammonium chloride	Fabric softening and finishing	Enhances the texture and pliability of the textile.	
Distearyl dimethyl ammonium chloride	Softeners and antistatic agents	Reduces friction between fibers and prevents static buildup.	
Alkyl benzyl dimethyl ammonium chloride	Washing and detergent formulations	Acts as a surfactant to enhance cleaning efficiency.	
Octadecyl trimethyl ammonium bromide	Anti-pilling finishes	Reduces the formation of pills on fabric surface.	
Cetyl trimethyl ammonium bromide (CTAB)	Softening process	Acts as a fabric softener by reducing static cling and improving hand feel.	

B. Imidazolinium Compounds

Imidazolinium compounds represent the second most prevalent cationic structures in detergent and softener formulations, following quaternary ammonium compounds. These molecules feature a characteristic substitution pattern: a fatty acid amido ethyl chain at the 1-position, a long-chain alkyl substituent at the 2-position, and a methyl group at the 3-position of the imidazoline ring. Unlike their quaternary ammonium counterparts, these imidazolinium compounds exclusively incorporate methyl sulfate as their counter-ion. Among these compounds, tallow-alkyl derivatives dominate commercial applications. The hydrogenated tallow chain variants deliver superior softening performance compared to their non-hydrogenated counterparts, though they present greater complexity in finished product formulation. Recently, oleyl derivatives have gained significance due to their reduced hydrophilizing effect while maintaining satisfactory softening performance. This allows treated textiles to retain most of their natural moisture absorption properties. In practical applications, these imidazolinium compounds are frequently combined with distearyl dimethyl ammonium compounds to achieve enhanced performance characteristics [29].



[Fig.6: 1-(Fatty Acid Amido Ethyl)-2- (Fatty Alkyl)-3-Methyl-Imida- Zolinium Methyl Sulphate]

To produce imidazolinium compounds, we first start with fatty acid and diethylenetriamine. They are condensed under ring closure, and the imidazoline formed is then converted with dimethyl sulphate to the imidazolinium salt. By condensing triethylenetetramine with fatty acids and subsequent ring closure with additional acid, 1,3-bis (fatty acid amido ethyl)- 2-alkyl-imidazolinium salts are obtained [30].

C. Amidation Reaction

Fatty Axid Reacts with N-(2-aminoethyl) ethylenediamine, forming an amide intermediate.

$$R\text{-}COOH + H_2N\text{-}(CH_2)_2\text{-}NH\text{-}(CH_2)_2\text{-}NH_2 \rightarrow R\text{-}C(=O)\text{-}N\text{-}(CH_2)_2\text{-}NH\text{-}(CH_2)_2\text{-}NH_2 + H_2O$$

D. Cyclization to Iimidazoline

The amide intermediate undergoes intramolecular condensation, losing two water molecules and forming an imidazoline ring.

$$R\text{-}C(=O)\text{-}N\text{-}(CH_2)_2\text{-}NH\text{-}(CH_2)_2\text{-}NH_2 \rightarrow R\text{-}C_3H_5N_2 + 2H_2O$$

E. Quanternization to Imidazolinium Salt

The imidazoline reacts with dimethyl sulfate to form the imidazolinium salt.$^-$

$$R\text{-}C_3H_5N_2 + (CH_3)_2\text{-}SO_4 \rightarrow R\text{-}C_3H_5N_2^+CH_3 + OSO_3^-$$

[Fig.7: Production of Imidazolinium Compounds]

IV. APPLICATIONS IN TEXTILE WET PROCESSING

A. Cationic Softeners

Imidazolinium compounds are widely employed as cationic fabric softeners due to their ability to impart a smooth, luxurious feel to textiles. Their softening action stems from their cationic nature; the positively charged group in their molecular structure attracts them to the negatively charged surface of textile fibers. Upon application, imidazolinium molecules adsorb onto the fibers, with their positively charged heads binding to the fiber surface and their hydrophobic tails extending outwards. These hydrophobic tails create a lubricating layer, reducing friction between individual fibers and allowing them to move more freely against each other.

This reduction in friction translates to a smoother, softer feel, improved drape, and a more pleasant handle. Beyond softening, imidazolinium compounds often provide antistatic benefits by attracting moisture to the fiber surface, creating a conductive layer that dissipates static electricity. Some imidazolinium softeners can even enhance wettability, improving the fabric's ability to absorb water. The degree of softening is influenced by factors like softener concentration, fiber type, and fabric construction. While effective, environmental concerns regarding the biodegradability of some imidazolinium compounds exist, prompting the development of more eco-friendly alternatives.

B. Antimicrobial Finishes

Benzalkonium chloride (BAC) and dodecyl dimethyl ammonium chloride (DDAC), both quaternary ammonium compounds (QACs), function as effective antimicrobial finishes by disrupting the cell membranes of microorganisms. Their cationic nature, stemming from a positively charged nitrogen atom, allows them to interact strongly with the negatively charged components of microbial cell membranes, primarily phospholipids. This interaction initiates when the positively charged QAC molecules are attracted to the negatively charged phosphate heads of the phospholipids within the membrane. Subsequently, the hydrophobic portion of the QAC molecule integrates into the lipid bilayer of the cell membrane, compromising its structural integrity. This disruption increases the membrane's permeability, leading to the leakage of essential cellular contents such as ions, proteins, and nucleic acids. The loss of these vital components disrupts essential metabolic processes within the microbial cell, ultimately resulting in cell death. Beyond membrane disruption, QACs can also interfere with other cellular functions, including protein synthesis and enzyme activity, further contributing to their antimicrobial efficacy [31].

The effectiveness of BAC and DDAC is influenced by factors such as concentration, contact time, the specific type of microorganism, and the presence of organic matter, which can hinder their activity. These QACs find wide application as antimicrobial finishes in textiles to prevent odour-causing bacteria, in cleaning products and disinfectants for hard surfaces, and in coatings for medical devices to inhibit pathogen growth. However, considerations regarding microbial resistance and environmental impact, particularly their potential effects on aquatic life, are important, driving the development of more biodegradable alternatives [32].

C. Anti-Static Agents

Static electricity can cause discomfort and safety concerns, particularly in synthetic textiles. Quaternary ammonium compounds (QACs) like Didecyl-dimethyl ammonium chloride, BAC are widely used as antistatic finishes due to their ability to mitigate the buildup of static electricity. Static charge arises from the transfer of electrons between materials during friction, leading to an imbalance of charges. QACs, being cationic, possess a positive charge that attracts moisture from the air, forming a thin, conductive layer on the treated material's surface.

This moisture layer acts as a pathway for the accumulated static charge to dissipate, preventing it from reaching levels that cause clinging or sparks. Applied as a finish, QAC molecules adsorb onto the material, their positive heads facing outward to readily attract and hold this moisture. This mechanism effectively reduces static cling, enhances comfort by preventing clothes from bunching up, minimizes dust attraction caused by static charge, and improves the overall appearance of fabrics by maintaining a smoother, less wrinkled look. While QACs offer effective antistatic protection, their durability can vary, and some may pose environmental concerns, prompting the development of more sustainable alternatives.

D. Emulsifiers in Scouring

During scouring, emulsification of oils, waxes, and dirt is critical for effective cleaning. Quaternary ammonium emulsifiers, such as cetrimonium bromide, play a significant role in this process. Their surface-active properties enhance the removal of impurities, ensuring better preparation of the fabric for subsequent processing stages.

E. Levelling Agents

Uniform dyeing is essential for achieving high-quality textiles. Benzalkonium chloride (BAC) plays a crucial role as a retarding agent in the dyeing of acrylic fibers with cationic dyes. Acrylic fibers possess negatively charged sites that attract the positively charged cationic dyes. BAC, also a cationic compound, competes with these dyes for the same sites. When added to the dye bath, BAC molecules preferentially occupy these negative sites on the fiber, effectively slowing down the dye uptake. This controlled competition prevents the dyes from immediately binding to the fiber, allowing for a more even and level distribution of colour. As the dyeing process progresses and the temperature increases, the BAC molecules gradually detach from the fiber, making way for the dye molecules to bind. This gradual release of dye sites ensures uniform penetration and prevents uneven or blotchy dyeing, ultimately improving colour evenness, depth, and overall dyeing quality. In essence, BAC acts as a temporary blocking agent, ensuring a more controlled and **optimised** dyeing process for acrylic fibers [33].

F. Fabric Conditioning

Esterquat-based formulations are frequently employed in fabric conditioning to enhance softness, reduce wrinkles, and improve drape. These compounds are applied during the rinse cycle or through padding techniques, contributing to the overall aesthetics and usability of the fabric.

G. Disinfectants in Wet Processing

In industrial textile settings, quats such as alkyl dimethyl benzyl ammonium chloride are used as disinfectants. These compounds effectively eliminate microbial contamination in processing equipment and fabrics, ensuring hygienic production environments. Their use is especially critical in pre-treatment processes.

H. Fixing Agents for Dyeing

Polydiallyl dimethyl ammonium chloride (polydadmac) acts as a crucial dye-fixing agent, particularly for reactive dyes on cellulosic fibers like cotton. Reactive dyes form strong covalent bonds with cellulose, resulting in excellent wash fastness. However, during dyeing, some dye molecules can hydrolyze, becoming less reactive and negatively impacting wash fastness due to their easier removal. Polydadmac, a cationic polymer, addresses this issue by forming complexes with these hydrolyzed dye molecules. Being positively charged, polydadmac strongly attracts the anionic hydrolyzed dye. When added after the dyeing process, polydadmac interacts with these hydrolyzed dye molecules through electrostatic attraction, creating larger, less mobile, and often insoluble complexes. These complexes effectively trap the hydrolyzed dye within the fiber structure, preventing them from bleeding or leaching out during subsequent washing. This significantly improves the wash fastness of the dyed fabric. Beyond wash fastness, polydadmac can also enhance rubbing fastness by reducing dye molecule mobility, minimize dye bleeding, and in some instances, improve overall dye exhaustion for deeper, more vibrant colours.

V. ENVIRONMENTAL IMPLICATIONS

Cationic surfactants, while effective in various applications, pose several environmental concerns:

A. Aquatic Toxicity

Cationic surfactants can be toxic to aquatic organisms, including fish, algae, and invertebrates. They can disrupt cell membranes and interfere with physiological processes, leading to adverse effects on growth, reproduction, and survival [34].

B. Sediment Contamination

Cationic surfactants tend to bind strongly to sediments, accumulating in the benthic environment. This can expose sediment-dwelling organisms to harmful levels of these chemicals and potentially disrupt the

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ecological balance of the sediment ecosystem [35].

C. Interference with Wastewater Treatment

Cationic surfactants can inhibit the activity of microorganisms in wastewater treatment plants, reducing the efficiency of the treatment process and potentially leading to the release of untreated or inadequately treated wastewater into the environment.

D. Persistence

Certain cationic surfactants resist degradation in the environment, meaning they do not readily degrade into less harmful substances. This can lead to their accumulation in water bodies and sediments over time, increasing the risk of long-term ecological effects [36].

E. Synergistic Effects

Cationic surfactants can interact with other pollutants in the environment, potentially enhancing their toxicity or leading to unexpected environmental impacts. This can make it challenging to predict and manage the overall risks associated with cationic surfactant contamination.

VI. RECENT ADVANCEMENTS

Recent advancements in textile science have led to the development of innovative materials and surfactants that enhance fabric properties while promoting sustainability. Three notable studies highlight progress in antibacterial cotton fabrics, sugar-based cationic surfactants for dyeing, and cationic Gemini surfactants for fabric softeners.

The study on antibacterial cotton fabrics explores the synthesis and application of biodegradable cationic silicone softeners to improve fabric properties. These softeners not only enhance fabric softness but also exhibit significant antibacterial properties against Staphylococcus aureus and Escherichia coli. The effectiveness of these softeners is influenced by variations in alkyl chain length, which affects hydrophilicity and overall performance. Additionally, the biodegradable nature of these softeners offers an environmentally friendly alternative to conventional textile finishing agents, aligning with the increasing demand for sustainable textile treatments. This research highlights the potential of biodegradable silicone softeners to enhance both fabric functionality and sustainability, contributing to eco-friendly advancements in textile manufacturing [37].

Another study presents the development of an environmentally friendly sugar-based cationic surfactant designed to function as a retarding agent in the dyeing of polyacrylonitrile (PAN) fibers. The surfactant is synthesized using a molecular design approach that incorporates partition coefficients and parachor parameters to optimize its performance. The surfactant regulates absorption by effectively competing with cationic dyes and prevents uneven dyeing in PAN fibers. Performance assessments using Methylene Blue (C.I Basic Blue 9) and Malachite Green (C.I Basic Green 4) demonstrate that the new retarder achieves effective dyeing results comparable to commercial alternatives. Additionally, the use of biodegradable materials in the surfactant reduces environmental pollution from dyeing processes, offering a sustainable alternative to traditional retarders. By improving dye uniformity while minimizing ecological impact, this research presents a promising advancement in sustainable textile dyeing solutions [38].

The study on cationic Gemini surfactants focuses on the synthesis, characterization, and application of a novel surfactant (C-16) in fabric softeners [39]. The surfactant is synthesized through a quaternization reaction, forming quaternary ammonium salts with enhanced performance properties. C-16 consists of two hydrophilic head groups and two hydrophobic tails connected by a spacer, providing superior surface-active properties [40]. The surfactant demonstrates a low surface tension (25.32 mN/m at 0.6% concentration), strong foaming properties, and a critical micelle concentration (CMC) of 24.78 mN/m. In fabric softener applications, the positively charged ammonium groups interact with fabric fibers, reducing friction and static while enhancing softness [41]. A 5% concentration is used in formulations with additional stabilizers like Glycerol Monostearate and Cetosteryl Alcohol. Beyond fabric softeners, Gemini surfactants have applications in cosmetics, home care, coatings, mining, and corrosion prevention, offering higher efficiency than traditional surfactants [42].

These studies showcase significant advancements in textile science, focusing on sustainable and high-performance materials. Biodegradable cationic silicone softeners enhance fabric softness and antibacterial protection, while sugar-based cationic surfactants improve dyeing processes with reduced environmental impact. The synthesis of Gemini surfactants for fabric softeners offers improved softness and stability, presenting a viable alternative to conventional surfactants. Collectively, these innovations contribute to the growing demand for eco-friendly textile treatments, paving the way for more sustainable industry practices.

VII. CONCLUSION

Cationic surfactants play a significant role in enhancing various textile processing operations, including dyeing, finishing, cleaning, and fabric softening. Their unique ability to interact with fabric surfaces and improve performance characteristics makes them invaluable to the textile industry. These surfactants possess positively charged hydrophilic groups that can adsorb onto negatively charged fiber surfaces, altering their properties and facilitating better interaction with dyes and other chemical treatments. The cationic nature of these surfactants allows them to form a protective layer on fabric fibers, reducing friction between fibers and enhancing the fabric's softness and durability. Additionally, their ability to modify surface properties can lead to improved wrinkle resistance, water repellence, and antistatic properties in treated textiles.

This characteristic improves dye uptake, colour fastness, and overall fabric quality. Additionally, cationic surfactants contribute to the softening and antistatic properties of fabrics, enhancing their comfort and wearability. However, challenges such as environmental impact and sustainability must be addressed to ensure the continued growth and application of these surfactants. Ongoing research into eco-friendly alternatives and greener

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processes promises a more sustainable future for textile processing, focusing on biodegradable formulations and reduced water consumption during manufacturing. Developing novel cationic surfactants with improved biodegradability and reduced toxicity is a key area of focus in current research. Scientists are exploring the potential of bio-based raw materials and green chemistry principles to create more environmentally friendly alternatives. These efforts aim to balance the performance benefits of cationic surfactants and the growing demand for sustainable textile processing methods.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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