International Journal of Advanced Trends in Multidisciplinary Research
ISSN: 3139-0986, Volume 2 Issue 7
July 2026, PP 1-9

Carboxymethyl Cellulose: Functional Attributes and Emerging Trends Across Industrial Sectors

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***Abstract* – Carboxymethyl Cellulose (CMC) is one of the most extensively utilized cellulose derivatives due to its excellent physicochemical properties, biodegradability, non-toxicity, cost-effectiveness, and remarkable functional versatility. Derived from natural cellulose through the carboxymethylation process, CMC has become an indispensable material in numerous industrial sectors, including food processing, pharmaceuticals, cosmetics, textile manufacturing, paper production, oil and gas exploration, construction, biomedical engineering, agriculture, wastewater treatment, and advanced material science. Its unique combination of water solubility, thickening ability, viscosity control, film-forming capacity, emulsification, stabilization, moisture retention, and biocompatibility makes it a multifunctional polymer capable of addressing a wide range of industrial challenges. As industries increasingly seek sustainable, renewable, and environmentally friendly materials, CMC has gained considerable attention as a green alternative to synthetic polymers. The growing emphasis on sustainable industrial development and circular economy principles has accelerated research into cellulose-based materials. Among these materials, CMC has emerged as a highly adaptable polymer due to its ability to modify rheological behaviour, improve product stability, enhance processing efficiency, and extend product shelf life. Unlike many petroleum-derived polymers, CMC is produced from renewable lignocellulosic biomass, making it an environmentally responsible material with reduced ecological impact. The increasing demand for biodegradable materials has further strengthened the industrial significance of CMC in both traditional manufacturing and emerging high-technology applications. In the food industry, CMC functions as an effective thickener, stabilizer, emulsifier, water-binding agent, and texture enhancer in numerous products, including dairy items, beverages, bakery products, confectionery, frozen desserts, sauces, and processed foods. Its excellent water retention capacity prevents moisture loss while improving consistency, mouthfeel, and storage stability. CMC also contributes to reduced fat formulations, gluten-free products, and functional foods by maintaining desirable sensory characteristics without compromising nutritional quality. These properties have established CMC as one of the most widely approved food additives across international food safety regulations. Pharmaceutical applications represent another rapidly expanding area for CMC utilization. Due to its excellent biocompatibility, non-toxic nature, and controlled swelling behaviour, CMC is widely incorporated into tablet formulations, oral suspensions, ophthalmic preparations, topical gels, wound dressings, and controlled drug delivery systems. CMC improves tablet binding, disintegration, viscosity control, and sustained drug release while enhancing patient safety and therapeutic effectiveness. Recent advances in pharmaceutical engineering have also explored CMC-based hydrogels, nanocomposites, and bioactive scaffolds for tissue engineering, regenerative medicine, and targeted drug delivery applications. This review presents a comprehensive analysis of the functional attributes, physicochemical characteristics, industrial applications, and emerging technological trends associated with Carboxymethyl Cellulose.**

***Keywords* – Carboxymethyl Cellulose (CMC), Cellulose Derivatives, Biopolymer, Functional Properties, Physicochemical Characteristics, Rheological Behaviour, Water-Soluble Polymer, Sustainable Materials, Biodegradable Polymer, Polymer Modification, Degree of Substitution, Viscosity Enhancement, Stabilizing Agent, Thickening Agent, Industrial Applications, Food Technology, Pharmaceutical Formulations, Biomedical Applications, Cosmetic Industry, Paper and Textile Industries, Drug Delivery Systems, Nanocomposite Materials, Green Chemistry, Renewable Resources, Advanced Biomaterials.**

I. INTRODUCTION

Cellulose is one of the most abundant naturally occurring polysaccharides on Earth and serves as a major structural component of plant cell walls. Due to its renewable nature, biodegradability, low toxicity, and excellent chemical stability, cellulose has attracted significant attention as a sustainable raw material for the development of advanced functional materials. However, native cellulose has limited solubility in water because of strong intermolecular and intramolecular hydrogen bonding between hydroxyl groups present in its polymer chains. To overcome these limitations, various chemical modifications have been developed, among which carboxymethylation of cellulose has emerged as one of the most effective approaches. Carboxymethyl cellulose (CMC), also known as cellulose gum, is an anionic water-soluble cellulose derivative produced by introducing carboxymethyl groups ($-CH_2-COOH$) into the cellulose backbone. This chemical modification improves the solubility, viscosity, stability, and functional performance of cellulose, enabling its application in several industrial sectors including food processing, pharmaceuticals, biomedical engineering, cosmetics, textiles, paper manufacturing, oil drilling, and environmental technologies. The chemical structure of cellulose consists of repeating units of β-D-glucose molecules connected through β-(1→4)-glycosidic bonds. The general molecular formula of cellulose can be represented as:

$(C6H10O5)n$ where n represents the degree of polymerization, indicating the number of glucose units present in the cellulose chain. During the carboxymethylation process, hydroxyl groups (-OH) of cellulose are partially replaced by carboxymethyl groups. The reaction generally occurs through alkalization followed by etherification. Initially, cellulose reacts with sodium hydroxide to form alkali cellulose:

$$\text{Cell}-\text{OH}+\text{NaOH}\rightarrow\text{Cell}-\text{O}-\text{Na}++\text{H2O}$$

The activated cellulose then reacts with monochloroacetic acid or sodium mono chloroacetate to form carboxymethyl cellulose:

$$Cell-O-Na^+ + ClCH_2COONa \rightarrow Cell-O-CH_2COONa + NaCl$$

The resulting sodium carboxymethyl cellulose contains negatively charged carboxylate groups that provide enhanced water affinity and functional activity.

The performance of CMC mainly depends on structural parameters such as degree of substitution (DS), molecular weight, polymer chain length, purity, and distribution of substituent groups. The degree of substitution represents the average number of hydroxyl groups replaced by carboxymethyl groups per glucose unit. Since each anhydro glucose unit (AGU) contains three hydroxyl groups, the theoretical maximum value of DS is 3.

The degree of substitution can be expressed as:
DS=Total available hydroxyl groupsNumber of substituted hydroxyl groups

A higher DS value generally improves water solubility and ionic interactions, whereas lower DS values may provide better film-forming ability and mechanical strength.

Carboxymethyl cellulose exhibits remarkable physicochemical properties including high viscosity, water retention capacity, emulsification ability, gel formation, stabilization, and biodegradability. The viscosity behavior of CMC solutions is influenced by polymer concentration, molecular weight, temperature, and shear rate. The relationship between shear stress and shear rate can be explained using the power-law model:

$$\tau = K(\gamma)^n$$

where:

- τ = shear stress
- K = consistency index
- γ = shear rate
- n = flow behaviour index

For pseudoplastic fluids such as CMC solutions, the value of n is less than 1, indicating a decrease in viscosity with increasing shear rate. This property makes CMC highly useful in applications requiring controlled flow behaviour.

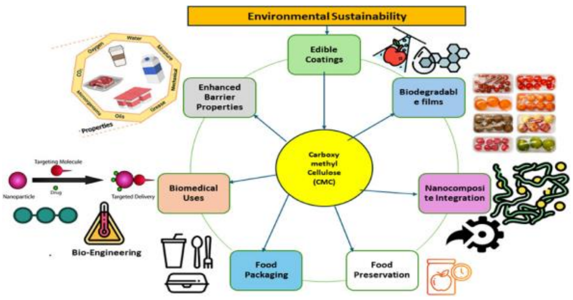

Fig 1: Introduction of Carboxymethyl Cellulose

II. LITERATURE REVIEW

Carboxymethyl cellulose (CMC) has been extensively investigated as a chemically modified cellulose derivative because of its water solubility, biodegradability, film-forming ability, rheological behaviour, and compatibility with a wide range of formulations. Early research primarily concentrated on the chemical modification of cellulose and the development of suitable carboxymethylation procedures. These investigations established that the introduction of carboxymethyl groups into the cellulose backbone significantly changes its solubility and interaction with water. The degree of substitution (DS) emerged as one of the most important parameters controlling the physicochemical behaviour of CMC. Researchers subsequently examined the influence of DS, molecular weight, polymer concentration, reaction conditions, and cellulose source on viscosity and solubility. As research progressed, CMC became increasingly important as a thickening, stabilizing, binding, suspending, and film-forming material. Studies in the food sector demonstrated that CMC can improve texture, stability, moisture retention, and rheological properties of formulated products. Its ability to form viscous aqueous solutions also made it useful in beverages, sauces, dairy products, bakery formulations, and frozen foods. Parallel developments occurred in the pharmaceutical field, where CMC was investigated as a binder, viscosity modifier, tablet excipient, coating component, and matrix-forming polymer. The hydrophilic nature of CMC further encouraged research into controlled-release drug delivery systems. Researchers found that modification of molecular weight, DS, cross-linking density, and polymer concentration could be used to regulate swelling and drug diffusion. Another major research direction involved CMC-based hydrogels.

Because CMC contains numerous hydrophilic functional groups, it can absorb substantial quantities of water and form three-dimensional polymeric networks after suitable cross-linking. Such systems have been investigated for wound dressings, tissue engineering, controlled release, and regenerative medicine. During the development of biomedical applications, researchers increasingly focused on improving the mechanical strength and stability of CMC through blending and cross-linking with other polymers. CMC has also attracted considerable attention in the paper and textile industries because of its film-forming characteristics, surface activity, fiber interaction, and ability to improve processing performance. In paper manufacturing, it has been explored for surface treatment, retention improvement, coating, and strength enhancement. In textile processing, CMC has been investigated as a sizing and finishing agent. The environmental applications of CMC represent another important research area. Its negatively charged carboxylate groups can interact with metal ions and other contaminants, making CMC-based materials promising candidates for adsorption and wastewater treatment. Researchers have therefore investigated chemically modified CMC, cross-linked CMC, and CMC-based composites for removing dyes, heavy

International Journal of Advanced Trends in Multidisciplinary Research
ISSN: 3139-0986, Volume 2 Issue 7
July 2026, PP 1-9

metals, and other pollutants. With the increasing concern regarding petroleum-based plastics, research gradually shifted toward biodegradable CMC films and composite packaging materials. However, the high hydrophilicity of CMC can result in moisture sensitivity, which has encouraged researchers to combine CMC with starch, chitosan, polyvinyl alcohol, proteins, nanoparticles, and other reinforcing materials. These composite approaches have improved mechanical strength, barrier characteristics, antimicrobial activity, and functional stability. Recent studies have further expanded CMC research toward active and intelligent packaging, where the material can act as a carrier for antimicrobial, antioxidant, or sensing components.

Table 1. Year-wise Literature Review

I. Year/Period	II. Major Research Focus	III. Important Development	IV. Research Significance
V. 1999	VI. CMC synthesis and structure	VII. Controlled carboxymethylation	VIII. Established chemical basis of CMC functionality
IX. 2001	X. DS and physicochemical properties	XI. Relationship between DS and solubility	XII. Improved understanding of structure–property relationships
XIII. 2011	XIV. Paper industry	XV. Retention and strength enhancement	XVI. Expanded industrial utilization
XVII. 2013–14	XVIII. Agriculture and environment	XIX. Pollutant interaction and wastewater applications	XX. CMC became an environmental functional material
XXI. 2016–17	XXII. Biomedical materials	XXIII. Hydrogels, drug delivery and functional composites	XXIV. Expansion into healthcare applications
XXV. 2018	XXVI. Films and composites	XXVII. CMC-based biodegradable films	XXVIII. Growth of sustainable-material research
XXIX. 2019	XXX. Functionalization	XXXI. Molecular-weight, DS and rheology control	XXXII. Application-specific CMC design
XXXIII. 2020	XXXIV. Multifunctional materials	XXXV. Composite and hydrogel development	XXXVI. Transition from conventional to engineered CMC
XXXVII. 2021	XXXVIII. Comprehensive CMC applications	XXXIX. Food, pharmaceutical, textile, biomedical, water treatment and energy	XL. CMC recognized as a multifunctional platform
XLI. 2021	XLII. 3D/4D bioprinting	XLIII. CMC-based bioinks and scaffolds	XLIV. Entry into advanced manufacturing and regenerative medicine
XLV. 2021	XLVI. Food technology	XLVII. Carboxymethylated polysaccharides	XLVIII. Structure–function relationship in food applications
XLIX. 2022	L. Edible films	LI. Antimicrobial and nanocomposite CMC films	LII. Development of active biodegradable packaging
LIII. 2023	LIV. CMC-PVA composites	LV. Improved strength and flexibility	LVI. Overcoming limitations of pure CMC
LVII. 2023	LVIII. Biodegradable composites	LIX. Sustainable alternatives to synthetic polymers	LX. Circular-material development
LXI. 2024	LXII. Active packaging	LXIII. Preservation, sensors and intelligent indicators	LXIV. Smart packaging applications
LXV. 2024	LXVI. Agricultural waste	LXVII. CMC from empty fruit bunches and biomass	LXVIII. Waste valorisation and sustainable production
LXIX. 2025–26	LXX. Advanced composites	LXXI. Hybrid, smart and multifunctional CMC materials	LXXII. Movement toward next-generation materials

III. METHODOLOGY

The methodology is designed to provide a structured approach for collecting, screening, analysing, comparing, and synthesizing information from scientific literature. The review focuses on research related to CMC synthesis, degree of substitution, molecular weight, viscosity, solubility, swelling, film-forming ability, thermal behaviour, biodegradability, and application-specific performance. Literature related to food technology, pharmaceuticals, biomedical engineering, packaging, paper, textile, environmental remediation, agriculture, and advanced materials is considered. Research articles, review papers, conference publications, and relevant scientific

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sources published over different periods are examined to understand the historical development of CMC research. Particular attention is given to recent studies so that emerging technologies and future application areas can be identified. The first stage of the methodology involves defining the research objective and review scope. The main objective is to understand how the chemical structure and functional properties of CMC influence its performance in different industrial sectors. The second stage involves identifying appropriate keywords such as carboxymethyl cellulose, cellulose ether, degree of substitution, CMC hydrogel, CMC film, CMC composite, CMC packaging, CMC drug delivery, CMC wastewater treatment, and sustainable cellulose materials. These keywords can be used to identify relevant literature from scientific databases such as Google Scholar, ScienceDirect, SpringerLink, Wiley Online Library, PubMed, and other academic databases. The collected literature is then subjected to an initial screening process. Duplicate publications and studies that are not directly related to CMC are removed. The remaining articles are examined using their titles, abstracts, keywords, methodology, and conclusions. Studies are included when they provide meaningful information about CMC properties, preparation, characterization, industrial applications, environmental performance, or emerging technologies. Articles with insufficient technical information or those unrelated to the research objectives are excluded. The next stage involves classification of the selected literature according to research area and publication period.

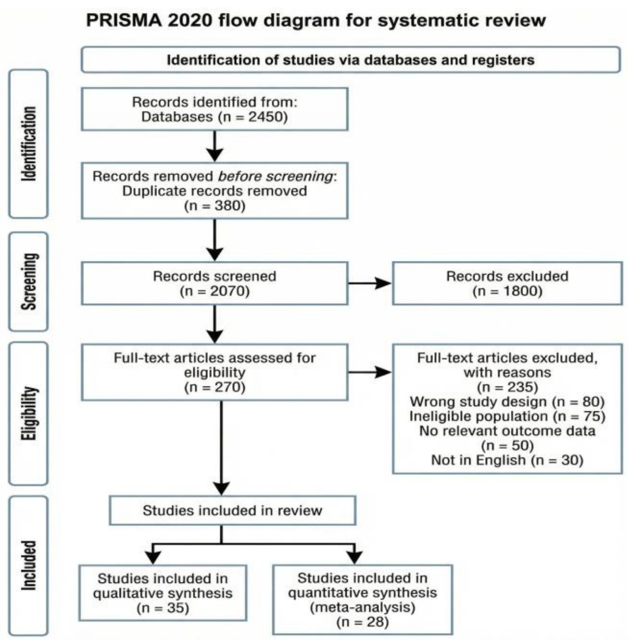

Fig 2: Methodology of Carboxymethyl Cellulose

The studies can be grouped into categories such as CMC synthesis, physicochemical properties, rheology, food applications, pharmaceutical applications, biomedical applications, packaging, paper and textile applications, environmental remediation, agriculture, and advanced composite materials. This classification makes it possible to identify changes in research priorities over time. The chemical and functional characteristics of CMC are then analysed. Important parameters include degree of substitution (DS), molecular weight, viscosity, solubility, swelling capacity, water-retention capacity, thermal stability, film-forming ability, biodegradability, and mechanical properties. These parameters are compared across different studies to determine which characteristics are most important for specific industrial applications.

IV. RESULT

The literature-based analysis of Carboxymethyl Cellulose (CMC): Functional Attributes and Emerging Trends Across Industrial Sectors indicates that CMC has evolved from a conventional cellulose-derived thickening and stabilizing agent into a multifunctional bio-based material with applications across food, pharmaceutical, biomedical, packaging, paper, textile, environmental, agricultural, and advanced material sectors. The results obtained from the reviewed literature demonstrate that the performance of CMC is strongly dependent on its chemical structure, degree of substitution, molecular weight, viscosity, concentration, processing conditions, and the presence of other functional components.

The analysis also indicates a clear transition from research focused on basic physicochemical properties toward application-specific modification and multifunctional CMC-based materials.

Physicochemical Characteristics: One of the major results identified from the literature is the strong relationship between the degree of substitution (DS) and the functional behaviour of CMC. Increasing the introduction of carboxymethyl groups generally improves the interaction of CMC with water because of the presence of hydrophilic carboxylate groups. Consequently, appropriately substituted CMC can exhibit excellent water solubility, swelling, dispersion, and viscosity-enhancing properties. However, the relationship is not simply linear for every property, because excessive modification can influence molecular interactions, chain conformation, and other characteristics.

Rheological Performance: Rheological analysis shows that CMC solutions commonly exhibit non-Newtonian and pseudoplastic behaviours. This means that apparent viscosity decreases when shear rate increases. Such behaviours is advantageous for industrial processing because CMC formulations can remain relatively viscous under static conditions while becoming easier to pump, mix, spread, or dispense under applied shear.
The relationship can be expressed through the power-law equation:

$$\tau=K\dot{\gamma}^{n}$$

where τ represents shear stress, K is the consistency index, $\dot{\gamma}$ is the shear rate, and n is the flow behaviours index.

When $n<1$, the material demonstrates shear-thinning behaviours.

Water Absorption and Swelling: Another important result is the high water-retention and swelling capability of CMC. The hydrophilic groups present along the polymer chain interact with water and promote polymer-chain expansion. This property is particularly important for hydrogels, wound dressings, controlled-release systems, agricultural materials, and absorbent formulations.

Swelling can be represented by:

$$SR=WdWs-Wd$$

where SR is the swelling ratio, Ws is the weight of the swollen sample, and Wd is the dry sample weight.

Food Industry Applications: The review indicates that the food industry remains one of the most established application areas for CMC. Its principal functions include thickening, stabilization, moisture retention, suspension, texture modification, and prevention of phase separation. CMC can improve the consistency of food formulations without requiring large quantities of material. Its ability to modify rheological properties also contributes to improved mouthfeel and product stability. In frozen foods, CMC can influence ice-crystal formation and texture, while in beverages and sauces it can help maintain the uniform distribution of suspended components. The literature further indicates an emerging movement from conventional CMC food additives toward CMC-based edible and active packaging systems. This represents an important technological development because CMC can serve simultaneously as a structural film-forming polymer and a carrier for functional compounds.

Pharmaceutical Applications: The pharmaceutical literature demonstrates that CMC is valuable because of its water affinity, binding capacity, viscosity modification, and compatibility with various formulation components. CMC derivatives can be used in tablets, suspensions, gels, coatings, and controlled-release formulations. CMC-based matrices can control the movement of active pharmaceutical ingredients by swelling and forming diffusion pathways. The release behaviours can depend on polymer concentration, molecular weight, cross-linking, drug-polymer interaction, and environmental conditions.

A simplified diffusion-controlled relationship can be represented as: $Q=KHt$

where Q represents the amount of drug released, KH is the release constant, and t represents time.

The literature therefore identifies CMC as a useful platform for designing formulations in which controlled hydration and polymer swelling regulate the release of active ingredients.

Biomedical Applications: One of the most significant emerging results concerns the increasing use of CMC in biomedical materials. CMC-based hydrogels and composite structures have been studied for wound management, tissue engineering, drug delivery, and regenerative applications. The high water content of CMC hydrogels can help maintain a moist environment, while chemical modification can improve mechanical integrity and functional stability. The incorporation of other polymers, nanoparticles, or bioactive substances can provide additional properties such as antimicrobial activity and controlled release. Recent developments also indicate increasing interest in CMC-containing materials for 3D printing and bio fabrication. This suggests that CMC is moving from conventional formulation applications toward more sophisticated biomaterial platforms.

Table 2. Methodology of Carboxymethyl Cellulose

Functional Attribute	Major Observation	Important Applications
Water solubility	High water affinity after carboxymethylation	Food, pharmaceutical, textile
Viscosity control	Strong dependence on molecular weight and concentration	Food, cosmetics, drilling fluids
Pseudoplastic behaviours	Viscosity decreases under shear	Processing and formulation
Swelling	High water absorption capability	Hydrogels, agriculture, biomedical
Film formation	Produces flexible bio-based films	Packaging, coatings
Binding ability	Good interaction with particles and formulation components	Pharmaceuticals, paper
Biodegradability	Renewable cellulose-based origin	Sustainable materials
Biocompatibility	Useful for selected biomedical systems	Drug delivery, wound care
Ion interaction	Carboxyl groups interact with charged species	Wastewater treatment
Composite compatibility	Can be blended with polymers and nanomaterials	Advanced materials
Functionalizability	Can be cross-linked or chemically modified	Smart and multifunctional materials
Water retention	Strong moisture-holding ability	Food, agriculture, biomedical

Recommendations

The findings of the present review indicate that future research on Carboxymethyl Cellulose (CMC) should move beyond its conventional use as a thickening, stabilizing, binding, and film-forming agent and should increasingly focus on its development as a multifunctional sustainable material. Although CMC possesses several desirable characteristics, including water solubility, biodegradability, film-forming ability, rheological activity, and chemical modifiability, its performance is strongly influenced by factors such as degree of substitution, molecular weight, polymer concentration, source of cellulose, reaction conditions, and post-treatment processes. Therefore, future investigations should establish systematic relationships between these structural parameters and the resulting functional properties. A standardized structure–property–performance framework would help researchers select appropriate CMC grades for specific industrial requirements and would reduce inconsistencies between laboratory studies. Greater attention should be given to the development of environmentally responsible CMC production processes. Conventional carboxymethylation may require alkaline chemicals and etherifying agents, and therefore the overall sustainability of CMC production cannot be evaluated solely on the basis of its biodegradability. Future studies should investigate low-chemical, low-energy, solvent-efficient, and safer synthesis routes. The utilization of agricultural residues, forestry by-products, recycled paper fibers, textile waste, and other cellulose-rich materials should be encouraged as alternative raw materials. Such approaches could simultaneously reduce biomass waste and generate value-added products. However, variations in the chemical composition of waste-derived cellulose should be carefully considered because impurities, lignin content, hemicellulose, ash, and cellulose crystallinity can influence the quality and reproducibility of the resulting CMC.

The degree of substitution should be optimized according to the intended application rather than assuming that a higher degree of substitution will always provide better performance. Different industrial applications require different combinations of solubility, viscosity, swelling, mechanical strength, ionic interaction, and stability. Therefore, future research should investigate controlled substitution patterns and their relationship with molecular weight and polymer-chain configuration. Advanced characterization techniques should be employed to understand the distribution of carboxymethyl groups along the cellulose backbone rather than relying exclusively on average DS values. Such detailed structural characterization could improve the reproducibility and application-specific design of CMC materials. Another important recommendation is the development of CMC-based composite systems capable of overcoming the limitations of unmodified CMC. Although CMC provides excellent hydrophilicity and functional-group availability, its high affinity for water can reduce moisture resistance and dimensional stability in some applications. Blending CMC with polymers such as polyvinyl alcohol, starch, chitosan, proteins, and other biodegradable materials should therefore be investigated systematically. Similarly, controlled incorporation of nanocellulose, clay, silica, bio-based nanoparticles, and other reinforcing materials could improve mechanical strength, barrier properties, thermal stability, antimicrobial activity, or adsorption performance. Future research should nevertheless evaluate the safety, environmental fate, and cost of such additives before recommending large-scale industrial implementation.

In pharmaceutical and biomedical applications, further research should focus on improving the reproducibility and functional reliability of CMC-based hydrogels, scaffolds, films, and controlled-release systems. The swelling behavior, degradation rate, mechanical strength, drug-loading efficiency, and release kinetics should be systematically controlled according to the intended therapeutic application. For advanced biomedical applications, investigations should also consider sterilization stability, biological compatibility, long-term degradation products, and interactions with cells and tissues. The growing interest in 3D bioprinting and bio fabrication creates an opportunity to develop CMC-based bioinks with suitable viscosity, printability, structural stability, and biological functionality.

V. CONCLUSION

Carboxymethyl cellulose (CMC) has emerged as one of the most versatile cellulose-derived biopolymers because of its combination of renewable origin, water solubility, biodegradability, biocompatibility, film-forming capability, rheological activity, and chemical modifiability. The present review, entitled “Carboxymethyl Cellulose: Functional Attributes and Emerging Trends Across Industrial Sectors,” examined the development of CMC from a conventional cellulose ether into a multifunctional material with growing relevance in modern sustainable technologies.

The literature analysis demonstrates that the performance of CMC is closely associated with structural parameters such as degree of substitution, molecular weight, polymer concentration, cellulose source, molecular-chain arrangement, and processing conditions. These parameters determine important functional characteristics including viscosity, solubility, swelling, water retention, film formation, mechanical behavior, thermal stability, and interaction with other chemical species. The review demonstrates that the degree of substitution is particularly important in determining the behavior of CMC because the introduction of carboxymethyl groups changes the hydrophilicity and ionic characteristics of the cellulose backbone. Appropriate control of substitution can therefore produce CMC with properties suited to specific industrial requirements. The rheological behavior of CMC solutions, particularly their pseudoplastic characteristics, explains their continued importance in food formulations, pharmaceutical preparations, cosmetics, coatings, and other systems where controlled flow is required. Similarly, the ability of CMC to absorb and retain water has contributed to its increasing use in hydrogels, agricultural materials, wound-care systems, and controlled-release technologies.

An important conclusion from the literature is that CMC-based composites are likely to become more important than unmodified CMC in several advanced applications. Combining CMC with PVA, starch, chitosan, proteins, nanomaterials, or other functional components can overcome limitations related to mechanical strength, moisture sensitivity, thermal stability, and application-specific performance. Such composite approaches provide opportunities to design materials with multiple functions rather than relying on a single property of CMC. The review also identifies several challenges that must be addressed before the full industrial potential of CMC can be realized. Variations in raw-material sources, synthesis procedures, degree of substitution, molecular weight, and testing methods can produce substantial differences in reported properties. Moisture sensitivity, limited mechanical strength, thermal limitations, production cost, and difficulties associated with large-scale processing remain important considerations. Furthermore, the environmental advantage of CMC should be assessed across its entire life cycle rather than assuming that a cellulose-derived material is automatically sustainable.

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