



Synthesis and Characterization of Interpolymer Complexes for Soil Structuring and Water Retention: A Materials Engineering Approach toward Sustainable Development Goals (SDGs)

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ABSTRACT

This study aims to synthesize and characterize interpolymer complexes for soil structuring and moisture retention from a sustainable materials engineering perspective. Sodium carboxymethylcellulose and a urea-formaldehyde oligomer were used as complementary polymer components to form interpolymer networks. The synthesized materials were evaluated using physicochemical characterization, Fourier-transform infrared spectroscopy, microscopy, swelling-related evaluation, and soil filtration testing. The results demonstrate that the interpolymer complexes modify soil-water behavior by reducing filtration rates and increasing filtration times under different treatment conditions, indicating their potential for improved water retention. The observed performance is associated with interactions between complementary polymer components that form stable structures capable of regulating water movement in soil. The findings demonstrate the potential of interpolymer complexes as functional materials for soil and water management. Their application has potential to contribute to more efficient irrigation-water use and sustainable soil-water management, providing materials-engineering support for Sustainable Development Goals (SDGs) related to food security and water management.

1. Introduction

Polymeric materials are increasingly developed as functional materials for environmental and agricultural applications because their physicochemical properties can be tailored through molecular

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composition, functional groups, and intermolecular interactions [1]. In soil engineering, polymer-based materials are particularly attractive because they can modify water transport, improve water retention, and contribute to the stabilization of soil structure. Hydrophilic polymers applied to sandy soils, for example, can substantially influence water retention and hydraulic behavior, demonstrating the importance of polymer–water–soil interactions in controlling soil moisture [2]. Sodium carboxymethylcellulose (Na-CMC) is especially promising for such applications because of its hydrophilic character, biodegradability, water affinity, and ability to form networks through interactions with complementary compounds [3].

Interpolymer complexes provide another approach to tailoring polymer functionality. These complexes are produced through interactions between complementary macromolecules and can exhibit physicochemical characteristics different from those of their individual components. Such interactions enable the development of structured polymer networks with potential applications in environmental protection and water-resource management [4]. In the present system, Na-CMC provides functional groups capable of participating in intermolecular interactions, whereas urea-formaldehyde oligomers can contribute to network formation. The chemistry and structural development of urea-formaldehyde systems are strongly influenced by their synthesis and polycondensation behavior [5]. Combining these components therefore offers a potential route for producing functional materials capable of modifying soil structure and water movement.

The application of functional polymer materials to soil is particularly relevant because soil degradation and inefficient water use remain important constraints on sustainable agriculture. Agricultural soil erosion affects soil functionality and associated biogeochemical processes [6], while inadequate moisture retention can increase irrigation requirements and water losses. Polymer-based soil conditioning can address these challenges by modifying the physical environment surrounding soil particles and controlling water transport. However, evaluating these materials solely from their macroscopic performance provides limited information regarding the mechanisms responsible for their behavior. Establishing relationships among molecular interactions, material morphology, and soil-level performance is therefore essential for the rational development of interpolymer materials.

Material characterization is consequently an important component of interpolymer-complex development. Fourier-transform infrared (FTIR) spectroscopy can identify changes in functional groups associated with polymer interactions, while morphological examination provides information on the organization and distribution of the resulting material. Rheological, swelling, stability, and filtration evaluations can further connect molecular and structural characteristics with practical performance. A combined characterization strategy is particularly useful because interpolymer systems depend on multiple interactions that collectively determine their physicochemical and functional properties [7].

Despite the potential of polymer-based soil conditioners, an integrated assessment connecting the formation and characterization of interpolymer complexes with their actual influence on soil water behavior remains important. Previous studies have established the usefulness of CMC-based materials and polymer systems for water management, but understanding how complementary polymer interactions translate into soil-level functionality is necessary for designing more effective materials. Such knowledge is also relevant to sustainable development because improvements in soil moisture management can contribute to efficient resource utilization. More broadly, technological innovation and sustainability-oriented approaches have increasingly been recognized as important components of strategies supporting sustainable development [8].

Therefore, this study aims to synthesize and characterize interpolymer complexes based on sodium carboxymethylcellulose and urea-formaldehyde oligomer and to evaluate their potential for soil structuring and moisture retention. The study integrates physicochemical characterization,

spectroscopic analysis, morphological observation, and soil filtration testing to examine the relationship between material formation and functional performance. The principal contribution is the integrated evaluation of molecular-level interactions and macroscopic soil-water behavior within a single materials-engineering framework. The resulting understanding is expected to support the development of functional polymer materials for more efficient soil and water management and to contribute to Sustainable Development Goals (SDGs) associated with food security and sustainable water use.

2. Literature Review

2.1 Interpolymer Complexes as Functional Materials

Interpolymer complexes are formed through interactions between chemically complementary macromolecules. Depending on the functional groups involved, complex formation can occur through hydrogen bonding, electrostatic attraction, ionic association, and other intermolecular interactions. These interactions can substantially modify the physicochemical behavior of the individual polymers and produce materials with improved stability, responsiveness, and functional performance. Recent developments in interpolymer-complex preparation demonstrate that controlling polymer composition and interaction conditions is essential for obtaining stable structures with desirable properties [9].

For soil-related applications, interpolymer systems are attractive because their network structures can interact simultaneously with water and soil particles. Such behavior may alter water mobility, improve moisture retention, and strengthen the physical association among soil components. The performance of these materials is therefore determined not only by the properties of the individual polymers but also by the nature and extent of the interactions developed during complex formation.

2.2 Sodium Carboxymethylcellulose in Polymer Networks

Sodium carboxymethylcellulose (Na-CMC) is a water-soluble cellulose derivative containing hydroxyl and carboxymethyl groups that provide strong affinity toward water and enable interaction with other polymeric components. Its solution behavior is influenced by concentration, molecular characteristics, and environmental conditions. Changes in these parameters can substantially affect viscosity and consequently influence polymer mixing, network formation, and material processing [10].

The hydrophilic nature of Na-CMC is particularly advantageous for soil-moisture applications because the polymer can interact with water while simultaneously participating in the formation of a polymeric matrix. When combined with a complementary oligomer, Na-CMC can contribute functional groups for intermolecular association and help form a continuous or microheterogeneous network. The resulting structure has potential to regulate water movement and improve the residence of moisture within treated soil.

2.3 Molecular Interactions and Stability of Polymer Complexes

The stability of polymer complexes depends on the balance among polymer composition, functional-group availability, hydrophilicity, and intermolecular interactions. Studies of polyelectrolyte complexes have shown that changes in polymer characteristics can influence the mechanism and stability of complex formation [11]. For the Na-CMC/urea-formaldehyde system

investigated in this study, hydroxyl, carboxyl, amino, and carbonyl-containing groups provide potential interaction sites that can contribute to network development.

Characterizing these interactions is essential because macroscopic properties such as swelling, moisture retention, mechanical stability, and resistance to environmental exposure originate from molecular-level organization. Consequently, spectroscopic and morphological analyses should be considered together with functional soil testing rather than evaluated independently. Such an integrated approach allows the material structure to be connected directly with its practical behavior.

Table 1

Functional efficiency comparison between manual methods and digital information systems

Performance Indicator	Manual Method (Baseline)	Digital System (Proposed)	Efficiency Gain (%)
Data Entry Duration (Average)	5 min 40 sec	1 min 15 sec	78.7%
Record Retrieval Speed	320.0 sec	12.0 sec	96.2%
Error Rate (per 100 entries)	4.2	0.2	95.2%
User Satisfaction (1–5 scale)	2.1	4.8	128.5%
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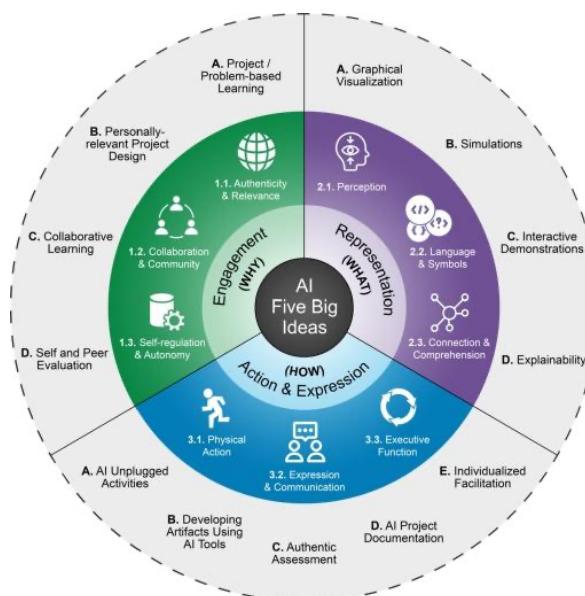


Fig. 1. AI-based framework for optimizing inclusive education processes. Figure was adopted from Omonova *et al.*, [17]

3. Methodology

3.1 Materials and Preparation of Interpolymer Complexes

The study employed an experimental approach using sodium carboxymethylcellulose from industrial production and a carbamide-formaldehyde oligomer as precursor materials. Figure 1 presents the molecular structure of sodium carboxymethylcellulose used as a base polymer component in the formation of the interpolymer complexes. The presence of hydroxyl and

carboxymethyl functionalities provides potential interaction sites for association with complementary groups in the carbamide-formaldehyde oligomer.

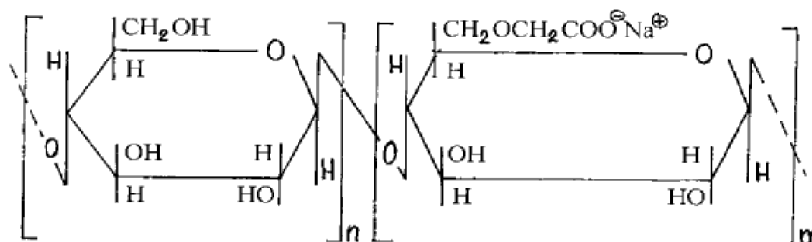


Fig. 1. Sodium salt of carboxymethylcellulose

The physicochemical characteristics of the carbamide-formaldehyde oligomer are summarized in Table 1. These characteristics include appearance, gelatinization behavior, pH, water miscibility, swelling index, density, viscosity, free formaldehyde content, standard compliance, and production source. The interpolymer complexes were subsequently prepared through controlled interaction between the complementary polymer components to promote stable network formation.

The rheological behavior of Na-CMC is relevant during preparation because solution viscosity affects polymer mobility, mixing, and interaction with complementary components [10]. Therefore, the physicochemical characteristics of the precursor materials were considered as important factors governing formation of the resulting polymer network.

Table 1

Physicochemical characterization of the urea-formaldehyde oligomer

Parameter	Value / Description
Appearance	Homogeneous suspension, white to light yellow, without inclusions
Gelatinization time (s / 1000 S)	40–65
Gelatinization time (hours at 20°C)	10
pH (hydrogen ion concentration)	7–8.2
Water miscibility (20 ± 1°C)	Fully miscible (1:2 by volume)
Swelling index	1.463
Density (g/cm ³)	1.28
Viscosity (VZ-4, 20°C, s)	25–60
Free formaldehyde content (%)	≤1%
Standard compliance	GOST 14231
Production source	Chirchik-Maxam JSC, Uzbekistan

3.2 Physicochemical and Spectroscopic Characterization

Material characterization was performed using several complementary analytical techniques. Thermogravimetric analysis was applied to evaluate fixation processes and thermal behavior of the synthesized materials, following the characterization approach commonly applied to interpolymer systems [9]. Gravimetric analysis was used to determine hygroscopic moisture retention under controlled temperature conditions using standard drying procedures.

Fourier-transform infrared (FTIR) spectroscopy was conducted using an IRTracer-100 spectrometer within the spectral range specified in the experimental procedure. FTIR analysis was used to identify functional groups and changes associated with interactions among polymer components. Interpretation of FTIR spectra was based on the relationship between characteristic absorption bands and their corresponding molecular vibrations [12]. The technique is widely

applicable for distinguishing chemical and structural characteristics based on infrared spectral features [13].

Viscosity measurements were performed using a VZ-4 viscometer to evaluate the rheological properties of the polymer system. Potentiometric titration using an EV-74 ionomer was additionally performed to examine ionic interactions and system stability. These complementary analyses were selected to provide information regarding the relationship between chemical interaction, physical characteristics, and formation of the interpolymer network.

3.3 Morphological, Stability, and Soil Performance Evaluation

Morphological examination was performed to evaluate the structural organization and distribution of the synthesized interpolymer material. The resulting microstructure was subsequently interpreted together with spectroscopic results to assess whether molecular interactions were accompanied by formation of an integrated polymer matrix.

Chemical stability and durability were evaluated by exposing the synthesized samples to saline and aggressive environments containing mixed inorganic salts. Following exposure, the samples were examined for structural integrity, resistance to compression, and changes in mass after extraction processes.

Functional performance in soil was evaluated using filtration testing. The tests compared water movement through untreated soil and soil subjected to interpolymer-complex treatment. Treatments included application at the soil surface and at a depth of 40 cm. Filtration rate and filtration time were used as indicators of changes in water transport behavior. This combination of physicochemical characterization, spectroscopy, morphology, stability testing, and soil filtration evaluation was used to establish the relationship between interpolymer structure and functional soil-water performance.

4. Results and Discussion

4.1 FTIR Analysis and Interpolymer Complex Formation

The FTIR characteristics of Na-CMC and the carbamide-formaldehyde oligomer (KFO) are summarized in Table 2. The spectra contain absorption bands associated with hydroxyl, amino, carbonyl, carboxylate, methylene, and C–N-containing groups. These functional groups provide the molecular basis for interactions between the two polymer components and are therefore important for understanding the formation of the interpolymer system. FTIR analysis is particularly useful for polymeric materials because changes in characteristic absorption bands can be associated with differences in functional groups and their chemical environments [12,13].

Thus, Table 2 provides a molecular basis for understanding the compatibility of Na-CMC and KFO. The hydroxyl and carboxylate functionalities of Na-CMC coexist with amino and carbonyl-containing groups of KFO, creating favorable conditions for intermolecular association. The FTIR findings are consequently consistent with formation of an interconnected polymer system whose macroscopic characteristics are further supported by the morphological observations.

Table 2

Classification of absorption bands in IR spectra of Na-CMC and KFO

Na-CMC Wavenumber (cm ⁻¹)	Na-CMC Intensity	KFO Wavenumber (cm ⁻¹)	KFO Intensity	Functional Group Assignment
3450	Strong	—	—	OH
—	—	3445	—	NH ₂ (asymmetric)
—	—	3350	—	OH, NH ₂
2930	Medium	—	—	CH ₂
—	—	2966	Medium	CH ₂
1710	Medium	—	—	C=O
—	—	1650	—	C=O
1590–1600	Medium	—	—	COO ⁻
—	—	1585	Weak	NH ₂ , CN
1435	Medium	—	—	COO ⁻
—	—	1460	—	CN, CH ₂
1380	Trace	—	—	CH ₂
—	—	1400	Medium	CN, CH ₂
1340	Trace	—	—	CH ₂
—	—	1370	Trace	CH
1250	Trace	1250	Medium	CH ₂ , OCN, NH
1170	Shoulder	—	—	—
1150	Trace	1150	Medium	NH ₂
1090	Trace	—	—	—
—	—	1060	Trace	COH, CN
—	—	1020	Trace	CN, C–O
920	Trace	920	Trace	—

Na-CMC exhibits a strong band at 3450 cm⁻¹ assigned to OH groups, while KFO contains bands at 3445 and 3350 cm⁻¹ associated with NH₂ and OH/NH₂ functionalities. These groups are important because hydroxyl- and amino-containing sites can participate in intermolecular association. Na-CMC also shows characteristic carboxylate-related bands at 1590–1600 and 1435 cm⁻¹. In contrast, KFO contains a carbonyl-related band at 1650 cm⁻¹ and bands assigned to NH₂ and C–N-containing functionalities. The coexistence of these complementary functional groups provides potential interaction sites during complex formation.

The bands in the lower-wavenumber region further demonstrate the chemical complexity of the two components. Both materials exhibit a band at 1250 cm⁻¹, although with different intensities, while KFO contains additional C–N and C–O-related features at 1060 and 1020 cm⁻¹. These observations should be interpreted as evidence of the functional groups available for intermolecular association rather than, by themselves, proof of formation of a new covalent bond. This distinction is important because interpolymer complexes can be stabilized through several non-covalent and ionic interactions [14].

4.2 Formation Mechanism and Morphological Characteristics

The proposed formation mechanism of the interpolymer system is illustrated in Figure 2. The schematic describes matrix polycondensation of urea-formaldehyde in the presence of Na-CMC and distinguishes several conditions ranging from a low-concentration matrix solution to gel formation, a stoichiometric complex, and products containing excess polymer components. The representation is useful because it demonstrates that the final material is governed by both chemical composition and the relative proportion of the interacting components.

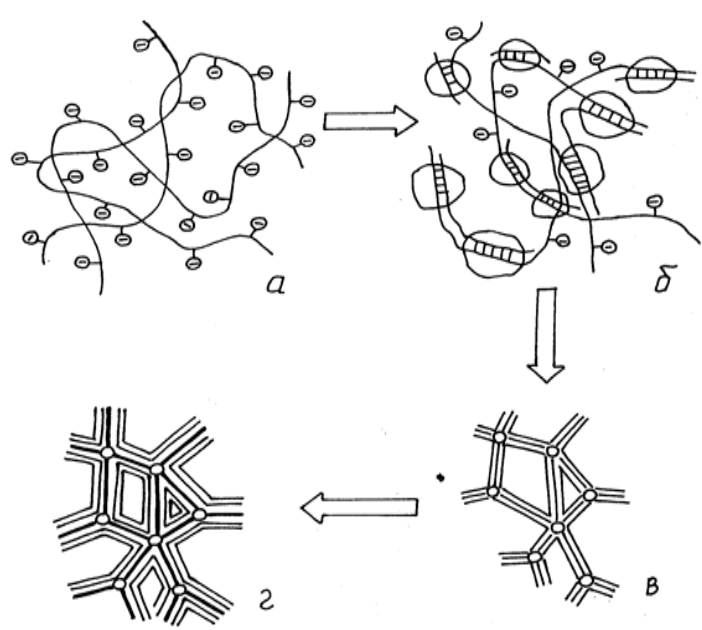


Fig. 2. Schematic illustration of formation of products formed by matrix polycondensation of urea formaldehyde with the participation of an oligomer and Na-CMC: (a) low-concentration matrix solution; (b) gel formation (product containing excess Na-CMC matrix); (c) stoichiometric complex; and (d) polycomplex and product containing excess carbamide-formaldehyde component

The proposed mechanism indicates progressive organization of the polymer components as the system moves from dilute conditions toward complex and gel formation. This behavior is compatible with the general characteristics of interpolyelectrolyte systems, in which molecular association can produce structures with properties that differ considerably from those of the isolated polymers [7]. The balance among functional groups, polymer concentration, and intermolecular association is therefore important for determining whether the resulting material behaves as a dispersed system, a gel-like structure, or a more developed polymer complex.

Morphological evidence supporting the formation of the material is provided in Figure 3. The micrographs show the hardened state of the material and its mixture with Na-CMC at a 1:1 ratio, obtained at 25°C. The images indicate the presence of fine dispersed structural features within a continuous matrix. This morphology is consistent with the formation of a microheterogeneous system rather than a simple physical separation of large polymer domains.

The relatively distributed morphology is important for functional performance because contact between the polymer matrix, water, and soil is influenced by the accessibility and distribution of hydrophilic domains. A heterogeneous but interconnected structure can provide sites for interaction with water while maintaining sufficient structural integrity to modify water transport through the treated soil. This interpretation is consistent with the broader development of cellulose-based water-absorbing materials for soil conditioning, where network structure is a central factor controlling water uptake and retention [15].

The combined evidence from Table 2, Figure 2, and Figure 3 therefore provides complementary information. FTIR identifies the functional groups capable of interaction; the schematic illustrates the proposed organization of the polymer components; and microscopy demonstrates the resulting morphology. Considered together, these observations establish a structure–function framework that can subsequently be related to the soil filtration results.

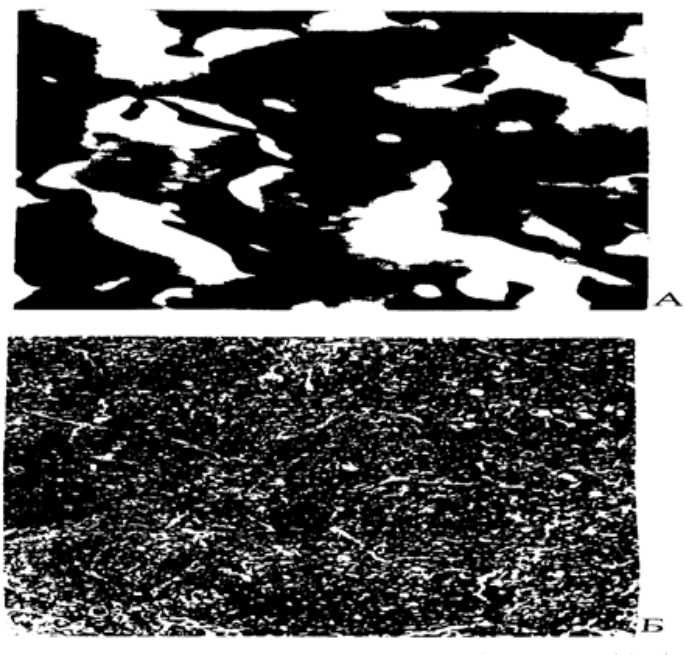


Fig. 3. Micrographs of the hardened state of RAJ (A) and its mixture with Na-CMC (B) at a 1:1 ratio ($\times 55$), obtained at 25°C

4.3 Soil Filtration and Water-Retention Performance

The practical effect of interpolymer-complex treatment on water movement through soil is shown in Table 3. Five tests were conducted using the same water volume of 1 L. The dataset compares untreated control soil with surface IPC treatment and IPC treatment applied at a depth of 40 cm. The results show substantial differences in filtration rate and filtration time among the three conditions.

A clear pattern is observed for the surface IPC treatment. In Test 1, the filtration rate decreases from 88.4 mm/min in the control soil to 51.00 mm/min after surface treatment, while filtration time increases from 12 to 26 s. The difference becomes progressively larger in the subsequent tests. By Test 5, the control filtration rate is 30.1 mm/min, whereas the surface-treated soil exhibits only 4.60 mm/min. At the same time, filtration time increases from 44 s for the control to 140 s for the surface-treated condition.

These data demonstrate that surface IPC application strongly restricts rapid water movement through the soil. A lower filtration rate accompanied by a longer filtration time indicates that water remains within or moves more slowly through the treated soil system. This behavior is consistent with the intended moisture-retention function of hydrophilic polymer-based soil conditioners. CMC-containing treatments have similarly been investigated for modifying soil water transport because their hydrophilic polymer networks can influence water-holding behavior and movement through soil [16].

The 40-cm depth treatment exhibits a different pattern. In Test 1, its filtration rate of 94.70 mm/min is slightly higher than the control value of 88.4 mm/min. However, in later tests the filtration rate decreases markedly. In Test 5, for example, the depth-treated soil has a filtration rate of 12.70 mm/min compared with 30.1 mm/min for the control. Filtration time simultaneously increases to 104 s compared with 44 s for untreated soil. Therefore, the effect of depth treatment becomes more evident across the sequential tests.

Comparison between surface and depth application also demonstrates the importance of treatment position. From Tests 2–5, the surface-treated condition consistently exhibits a lower filtration rate than the 40-cm depth treatment. In Test 5, the respective rates are 4.60 and 12.70 mm/min, while the corresponding filtration times are 140 and 104 s. Surface application therefore produces the strongest restriction of water movement within the conditions represented by this dataset.

This behavior can be explained qualitatively by the interaction between the hydrophilic polymer network and infiltrating water. Na-CMC-containing materials can interact strongly with water, while polymer-network formation can increase the residence of water within the treated region. CMC-based soil treatments have been reported to affect water transport and water-use characteristics in soils, supporting their potential application for moisture management [17]. Similarly, CMC-based hydrogel systems have been investigated specifically for improving water retention in soil [18].

Importantly, the present data demonstrate filtration behavior rather than direct agronomic responses such as plant growth or crop yield. Therefore, the results should not be interpreted as direct evidence of improved agricultural productivity. Instead, Table 3 provides experimental evidence that IPC treatment modifies soil-water transport, particularly by decreasing filtration rate and increasing filtration time. These changes establish the engineering basis for considering the material as a potential soil-moisture-management system.

Table 3

Filtration rate and water-retention performance of treated soils

Test No.	Water Volume (L)	Control Soil K (mm/min)	Control Soil t (s)	Surface IPC Treatment K (mm/min)	Surface IPC Treatment t (s)	Depth IPC Treatment, 40 cm K (mm/min)	Depth IPC Treatment t (s)
1	1	88.4	12	51.00	26	94.70	14
2	1	60.3	15	31.57	42	69.70	28
3	1	55.2	22	13.95	61	29.40	45
4	1	33.1	40	8.89	95	21.90	63
5	1	30.1	44	4.60	140	12.70	104

4.4 Materials Engineering and Sustainability Implications

Taken together, the spectroscopic, morphological, and filtration results demonstrate a relationship between polymer composition, structural organization, and soil-water performance. The complementary functional groups identified in Table 2 provide interaction sites; the formation mechanism in Figure 2 explains the development of the polymer network; Figure 3 demonstrates the resulting morphology; and Table 3 shows that application of the material alters water movement through soil. This integrated interpretation is more informative than considering each characterization result independently.

From a materials-engineering perspective, the findings indicate that Na-CMC-based interpolymer systems can be designed to regulate interactions among polymer, soil, and water. This concept is consistent with recent development of cellulose-based water-retention materials in which polymer-network engineering is used to improve soil moisture management [19]. The present results further indicate that application configuration matters: surface treatment produced a stronger reduction in filtration rate than treatment at 40-cm depth under most of the tested conditions. Thus, practical implementation should consider not only polymer composition but also placement within the soil profile.

The sustainability relevance of these materials arises primarily from their potential contribution to water management. Slower water transport and increased residence time can potentially support more efficient use of irrigation water in environments where moisture availability is limited. This engineering approach is consistent with the broader use of technological innovation to address sustainability challenges [8]. However, sustainability benefits should be interpreted cautiously because the present experiments evaluate material and soil-water behavior rather than long-term field performance, crop productivity, biodegradation, or life-cycle impacts.

Material characterization also provides an important foundation for future sustainable-material development. FTIR-based analysis, for example, can connect chemical characteristics with material-processing mechanisms and can be incorporated into broader sustainability-oriented materials research [20]. The combination of molecular characterization and functional testing used here therefore provides a basis for optimizing interpolymer complexes according to both material properties and environmental performance.

The synthesized interpolymer system shows potential as a functional material for regulating soil-water behavior, as demonstrated by the substantial decrease in filtration rate and increase in filtration time following IPC treatment. These effects are relevant to water conservation and sustainable soil management. From a broader sustainability perspective, this functionality is relevant to SDG 6 through its potential contribution to more efficient water use and may indirectly support SDG 2 by improving water-management conditions required for sustainable agricultural systems [8,20,21]. Further field-scale evaluation is required to establish long-term performance and quantify agricultural and environmental benefits under actual cultivation conditions.

5. Conclusion

Interpolymer complexes based on sodium carboxymethylcellulose and urea-formaldehyde oligomer showed functional potential for soil-water management. FTIR analysis identified complementary functional groups supporting intermolecular association, while morphological observations indicated formation of a microheterogeneous polymer structure. Soil filtration tests demonstrated that IPC treatment reduced filtration rates and increased filtration times, with surface application producing the strongest effect under most tested conditions. These findings establish a relationship between material structure and soil-water behavior and support the potential use of IPCs for moisture management. Further field-scale studies are required to evaluate long-term stability, environmental performance, and practical agricultural benefits under actual cultivation conditions.

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