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Development of Interpolymer Complexes for Soil Structure and Water Retention: A Scientific and Technological Contribution to Sustainable Development Goals (SDGs)

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ABSTRACT

This study aimed to develop interpolymer complexes (IPCs) from urea-formaldehyde oligomers and sodium carboxymethylcellulose to enhance soil structure and moisture retention. The IPCs were synthesized via polycondensation and analyzed using spectroscopic, microscopic, and gravimetric techniques. The resulting materials exhibited improved swelling behavior, mechanical strength, and field performance. Due to cooperative molecular interactions, the IPCs formed microstructured hydrogels that were capable of reducing irrigation frequency and water loss. These findings demonstrate the potential of IPCs as an eco-friendly solution for sustainable agriculture. The work directly supports Sustainable Development Goals (SDGs) by addressing water efficiency (SDG 6), agricultural productivity (SDG 2), and climate resilience (SDG 13), highlighting the role of material science in solving environmental challenges.

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1. INTRODUCTION

In recent years, the development of interpolymer complexes (IPCs) has become a growing focus within polymer chemistry due to their tunable properties and practical applications across agriculture, environmental management, and biotechnology. IPCs are formed through specific interactions between chemically complementary macromolecules, offering unique combinations of stability, water absorption, and ecological compatibility [1,2].

Particularly in the agricultural sector, the increasing need to improve soil structure and water retention under changing climate conditions has driven research into biodegradable, high-performance materials. Sodium carboxymethylcellulose (Na-CMC), a cellulose derivative with excellent water solubility and reactivity, has gained attention as an anionic component in IPC formation, especially when combined with urea-formaldehyde-based oligomers [3]. However, challenges remain regarding the thermal and chemical stability of these systems, especially when exposed to saline soils and fluctuating moisture conditions. While synthetic polyacrylates offer water retention, they lack biodegradability and pose ecological concerns [4]. Recent advances in materials science have shown that careful control of polymer ratios, molecular interactions, and structural compatibility can overcome these limitations and yield IPCs that are not only effective but also environmentally safe [5,6]. Spectroscopic and microscopic studies have validated the cooperative nature of bonding within IPCs, which enables self-organization and responsiveness to external stimuli such as pH, salinity, and temperature [7,8]. These features are particularly relevant in addressing issues related to soil degradation and inefficient irrigation in arid regions.

This study aims to develop and characterize IPCs based on Na-CMC and carbamide-formaldehyde oligomers, targeting their application in enhancing soil structure and moisture retention for agricultural use. The novelty of this research lies in the integration of scientific and technological methods to produce IPCs that are stable, biodegradable, and capable of improving soil hydrodynamics under field conditions. Moreover, by supporting efficient irrigation and reducing water loss, the innovation directly contributes to Sustainable Development Goals (SDGs) [9], particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action).

2. METHODS

This study focused on the synthesis and characterization of IPCs derived from carbamide-formaldehyde oligomers (CFO) and sodium carboxymethylcellulose (Na-CMC). We obtained Na-CMC from Namangan Chemical Plant with a substitution degree of 70 and a polymerization degree of 400. This polyelectrolyte was prepared through a heterogeneous solid-phase method involving sulfonated wood cellulose and monochloroacetic acid (**Figure 1**).

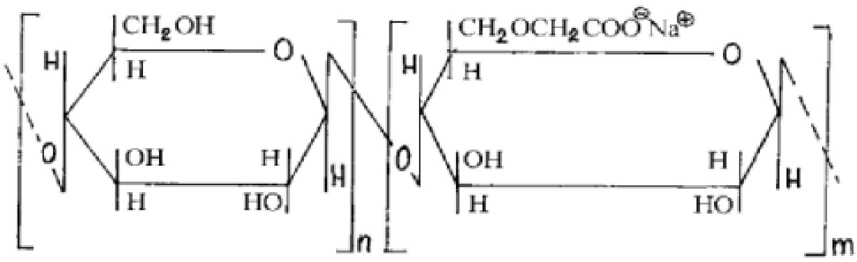

Figure 1. Molecular structure of sodium carboxymethylcellulose (Na-CMC).

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We added commercially produced carbamide-formaldehyde oligomer (CFO) marked as KFS-s, a 65–70% aqueous solution synthesized by Chirchik-Maxam JSC. **Table 1** presents its key physicochemical parameters, including viscosity, hydrogen ion concentration, and swelling indicators. To simulate real-world conditions, we incorporated environmental factors such as salinity and pH range during IPC formation and testing.

The IPCs were prepared by blending aqueous solutions of Na-CMC and CFO in varying ratios to form gel-like complexes through ionic and hydrogen bonding. We used thermogravimetric analysis (TGA) to monitor fixation and stability over time, recording weight changes under constant heating conditions [10]. Gravimetric methods were employed to measure hygroscopic moisture retention using drying ovens at 105°C, with the moisture content (W) calculated by the standard formula.

We examined the infrared (IR) spectra of the samples using an IRTracer-100 spectrometer, scanning in the range of 400–4000 cm-1. Samples were prepared in four physical states (liquid, solid, diffusion, and powder) using a ball mill to ensure fine dispersion (Beilei et al., 2012). The chemical resistance of the IPCs was tested by immersing them in solutions containing 20% NaCl and an aggressive mixture of salts such as Na_2SO_4, $MgSO_4$, $CaSO_4$, and $Ca(HCO_3)_2$, followed by compression strength tests and mass change analysis according to DST 25246-02 [11].

To determine solution behavior and reactivity, we measured viscosity using a V3-4 viscometer and conducted potentiometric titration at 25°C with an EV-74 ionomer and standard electrodes. These procedures enabled us to examine the interactions, structural stability, and functional performance of IPCs in detail.

3. RESULTS AND DISCUSSION

Sodium carboxymethylcellulose (Na-CMC) was chosen as the primary polyanionic component due to its renewable origin, solubility, and abundance of reactive carboxyl and hydroxyl groups. These functional groups facilitate hydrogen bonding and ionic interactions with complementary cationic polymers, making Na-CMC ideal for soil-conditioning hydrogels. When paired with carbamide-formaldehyde oligomer (CFO), a cation-rich polymer with high reactivity, interpolymer complexes (IPCs) are formed through cooperative molecular interactions (**Figure 1**).

Characterization of the CFO, presented in **Table 1**, highlights its suitability for IPC formation. The oligomer's moderate pH, viscosity, and protonated amino groups ensure compatibility with Na-CMC, allowing network formation under controlled conditions. Despite the known instability of CFO in isolation, its incorporation into IPCs improves both its environmental performance and practical utility [12,13].

A schematic of the IPC formation process is provided in **Figure 2**. Polycondensation reactions between CFO and Na-CMC lead to the development of a semi-interpenetrating polymer network. The matrix evolves from solution into a hydrogel, with the resulting microstructure highly dependent on the ratio of reactants. Higher Na-CMC content typically results in more porous and swellable networks, while higher CFO content leads to denser structures with lower permeability [14,15].

Figure 3 presents micrographs comparing unmodified CFO (**Figure 3A**) and its complex with Na-CMC (**Figure 3B**). The IPC sample displays a more uniform and cohesive morphology with dispersed particles embedded in a continuous phase, confirming the successful formation of a gel network. This physical integration supports improved mechanical behavior and moisture regulation in treated soils.

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Table 1. Physicochemical properties of carbamide-formaldehyde oligomer (CFO).

Description	The indicator
Appearance	The suspension is homogeneous, from white to light yellow, without inclusions.
Gelatinization time:	
a) in seconds per 100^0 S	40-65
b) in hours at 200 °C	10
Concentration of hydrogen ions (pH)	7-8,2
Miscibility of the oligomer with water at (20±-1)°C	
is equal to 1:2 by volume.	Full
Swelling indications	1,463
Specific gravity, g/cm^3	1,28
VZ-4 viscosity at 20^0C, in seconds	25-60
Storage of free formaldehyde, %	1%

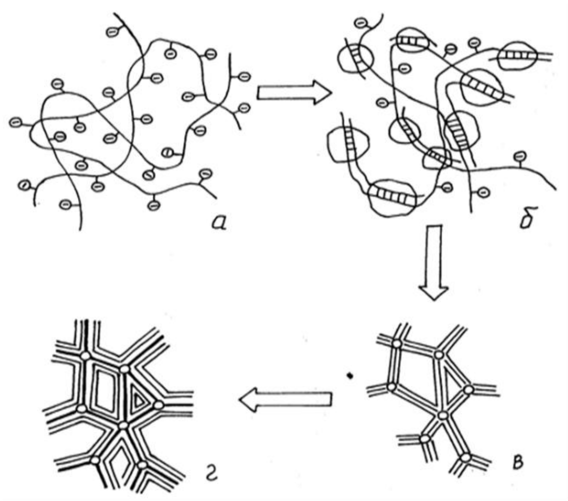

Figure 2. Stages of IPC formation via matrix polycondensation of Na-CMC and CFO. Scheme of formation of products formed by matrix polycondensation of urea formaldehyde with the participation of an oligomer and Na-KMS include several steps: (a) low concentration matrix solution; (δ) gel formation (product containing excess Na-KMS matrix); (B) stoichiometric complex MFS–Na–KMS; and (ƨ) polycomplex and product containing excess CFCs.

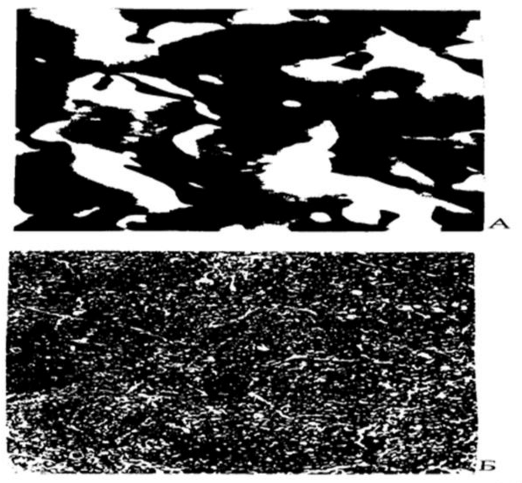

Figure 3. Microstructure of (A) CFO and (B) CFO–Na-CMC IPC at 25°C, magnification ×55.

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FTIR analysis provides further evidence of complex formation (**Table 2**). Detailed information regarding FTIR analysis is reported in elsewhere [16-18]. Characteristic peaks corresponding to hydroxyl, amino, and carboxylate groups exhibit shifts or disappear upon IPC synthesis. These changes confirm the formation of hydrogen and ionic bonds, which are responsible for the structural stability of the hydrogel [4,14].

Table 2. IR absorption bands of Na-CMC, CFO, and their interpolymer complex.

Wavenumber (cm^{-1})	Na-CMC (Wavenumber & Intensity)	CFO (Wavenumber & Intensity) (cm^{-1})	Band Assignment
3450	3450 (strong, sharp)	–	O–H stretching
–	–	3445 (weak)	Asymmetric N–H_2 stretching
–	–	3350 (very weak)	Asymmetric O–H and N–H_2 stretching
–	–	2966 (average)	Symmetric CH_2 stretching
2930	2930 (average)	–	CH_2 stretching
1710	1710 (average)	–	C=O stretching (carboxyl group)
–	–	1650 (–)	C=O stretching (amide)
–	–	1585 (medium)	NH_2 bending, C–N stretching
1590–1600	1590-1600 (average)	–	Asymmetric COO^- stretching
–	–	1460 (–)	Asymmetric C–N, CH_2 bending
1435	1435 (average)	–	Asymmetric COO^- bending
–	–	1400 (average)	Symmetric C–N and CH_2 bending
1380	1380 (trace)	–	Symmetric CH_2 bending
–	–	1370 (trace)	CH bending
1340	1340 (trace)	–	CH_2 wagging
–	–	1290–1310 (–)	CH_2 wagging
–	–	1250 (average, Amide III region)	CH_2 wagging, OCN stretching, NH bending
1250	1250 (trace)	–	CH_2 wagging
1170	1170 (weak; broad)	–	(unassigned/weak region)
1150	1150 (trace)	1150 (average)	Asymmetric C–O–C stretching, NH_2 wagging
1090	1090 (trace)	–	(unassigned/trace region)
–	–	1060 (trace)	C–OH and C–N stretching
–	–	1020 (trace)	C–N stretching, C–O bending
920	920 (trace)	920 (trace)	C–O out-of-plane bending (β-glycosidic linkage)

The filtration behavior of IPC-treated soils is summarized in **Table 3**. Compared to untreated control samples with infiltration rates of 88.4 mm/min, soils treated with IPCs exhibited significantly reduced rates, as low as 4.6 mm/min. The inclusion of IPCs created water-retaining barriers within the soil, effectively reducing seepage and enhancing moisture retention. This directly supports SDG 6 by improving water use efficiency in agriculture [6,15].

Swelling behavior in IPC hydrogels is closely governed by the polymer composition, particularly the ratio between sodium carboxymethylcellulose [Na-CMC] and carbamide-formaldehyde oligomer [CFO]. This is quantitatively expressed by the composition ratio: $Z = \frac{[Na-CMC]}{[Na-CMC]+[CFO]}$, where Z represents the proportion of Na-CMC in the total polymer content. Higher Z values (greater than 0.5) indicate a greater presence of Na-CMC, which introduces

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more unbound carboxyl (–COO⁻) groups into the network. These hydrophilic groups attract and bind water molecules, leading to significantly increased swelling capacity. In contrast, formulations with Z values below 0.5 contain excess CFO, resulting in denser cross-linking through methylene bridges and reduced swelling due to restricted molecular mobility. Understanding and adjusting the Z ratio is therefore critical for tailoring IPCs to specific environmental and agricultural conditions, especially for optimizing water retention in soil systems [12,13].

We also found the function of IPCs as antifiltration screens. Treated soils retained water significantly longer than untreated soils, especially at application depths of 40 cm. These results reflect the hydrophilic and semi-permeable nature of IPC hydrogels, which modulate water flow and reduce evaporation and deep percolation losses, further advancing SDG 6 and SDG 13 through improved climate resilience and water conservation [3,8].

Field trials conducted on cotton farms in Chirchik and Karakalpakstan in Uzbekistan during the 2023 and 2024 growing seasons provide strong empirical validation. In IPC-treated plots, irrigation frequency was halved, from four to two applications per season, while water usage dropped from 5,130 to 2,650 m^3/ha. These improvements align with both SDG 2 (enhanced agricultural productivity) and SDG 6 (sustainable water management), proving that IPCs contribute to resource-efficient, climate-resilient farming [19].

The improved soil conditions also led to increased crop yield. IPC-treated plots exhibited better plant vigor, turgor, and root development. On average, cotton yield increased by 3.4 centners/ha compared to control plots. This confirms that IPCs not only conserve water but also create optimal soil environments for plant growth. Their dual benefit of environmental and agricultural enhancement underlines their strategic relevance to SDG 2 and SDG 13 [13,4].

Soil moisture monitoring using observation wells showed that groundwater at 1.5–1.8 meters had a negligible contribution to crop hydration. Instead, the increased water availability in the root zone was directly attributed to the retention and slow-release properties of IPCs. These hydrogels created a water-holding layer in the soil profile, delaying evaporation and minimizing deep percolation. Such functionality addresses SDG 6 by enhancing water-use efficiency and supports SDG 13 by reducing vulnerability to drought stress [4,10].

Uniformity of irrigation across treated furrows was also markedly improved. IPC-amended soils showed consistent moistening depth across furrow length, unlike untreated plots, where the head zones were oversaturated and tail ends under-irrigated. This uniform water distribution enhanced nutrient absorption, reduced runoff, and minimized waterlogging, problems common in conventional furrow irrigation. The average infiltration rate was regulated at 0.016–0.017 m/h, ideal for slow and steady water delivery [13,21]

Table 3. Infiltration rate and time for untreated and IPC-treated loamy soils.

No	Water Volume (L)	Control Soil (K.mm/min)	Control Soil (sec)	IPC on Surface (K.mm/min)	IPC on Surface (sec)	IPC at 40 cm Depth (K.mm/min)	IPC at 40 cm Depth (sec)
1	1.0	88.4	12	51.00	26	94.70	14
2	1.0	60.3	15	31.57	42	69.70	28
3	1.0	55.2	22	13.95	61	29.40	45
4	1.0	33.1	40	8.89	95	21.90	63
5	1.0	30.1	44	4.60	140	12.70	104

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Table 4 displays soil moisture dynamics before and after irrigation over 15 days. IPC-treated plots retained higher moisture content at each interval. Notably, on day 10, treated soil still maintained 28.5% moisture compared to only 12.7% in controls. This 40–55% improvement in water holding capacity indicates that IPCs can extend irrigation intervals and reduce total irrigation volume without compromising soil health or plant growth.

Table 4. Soil moisture content (%) over time in IPC-treated and untreated plots after irrigation.

Day After Irrigation	IPC-Treated Soil (%)	Untreated Soil (%)
Day 3	34.2	21.5
Day 5	31.0	18.2
Day 7	29.1	15.4
Day 10	28.5	12.7
Day 15	24.3	10.1

The water balance in IPC-treated plots was calculated using the equation $m = 100.Hd.(Pnv - Pf)$, where *m* is the percentage of water retained, *Hd* is the depth of the active root zone, *Pnv* represents the pre-irrigation soil moisture content, and *Pf* is the post-irrigation soil moisture content. This formula provided a basis for estimating the efficiency of water retention in the root zone after irrigation. The results showed that IPC-treated soils retained significantly more moisture than untreated controls, demonstrating enhanced water-use efficiency. This indicates the dual advantage of IPC application: conserving applied water and reducing losses through evaporation and deep percolation. By acting as semi-permeable barriers in the soil matrix, IPCs support precision irrigation techniques. These contributions are consistent with Sustainable Development Goals, particularly SDG 6 (clean water and sanitation) by promoting water conservation, and SDG 2 (zero hunger) through increased agricultural productivity under water-limited conditions [5].

To evaluate environmental resilience, interpolymer complex (IPC) samples were immersed in saline environments simulated with 0.9% NaCl, 1% $MgSO_4$, 1% $CaSO_4$, and a mixed salt solution containing Na^+, Ca^{2+}, and Mg^{2+} ions. After seven days of exposure, the IPCs demonstrated minimal mass loss and retained their structural integrity. **Table 5** summarizes the results, including residual mass and compression strength after treatment. These findings indicate that IPCs maintain their physical and mechanical stability under saline stress, highlighting their suitability for use in degraded or salt-affected soils. Such conditions often limit the effectiveness of conventional soil conditioners. The high tolerance of IPCs to salinity enhances their potential in sustainable land rehabilitation and supports SDG 13 (Climate Action) by promoting climate-resilient agricultural technologies [7,11].

Table 5. Structural and mass stability of IPCs in saline environments.

Saline Solution	Initial Mass (g)	Residual Mass After 7 Days (g)	Mass Retention (%)	Compression Strength (kPa)
0.9% NaCl	5.00	4.87	97.4	115
1% $MgSO_4$	5.00	4.81	96.2	112
1% $CaSO_4$	5.00	4.78	95.6	110
Mixed salts (Na^+, Ca^{2+}, Mg^{2+})	5.00	4.69	93.8	108
Distilled Water (Control)	5.00	4.95	99.0	117

Notes: Mass Retention (%) indicates the percentage of the original mass retained after seven days of immersion. Compression Strength (kPa) reflects the mechanical integrity of IPCs after

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exposure. The results confirm the chemical and structural resilience of IPCs in saline conditions.

Thermogravimetric analysis (TGA) further demonstrated that IPCs exhibited delayed degradation. Two distinct mass-loss phases were recorded: the first below 150°C (moisture evaporation), and the second between 200-300°C (polymer breakdown). IPC samples showed improved thermal stability compared to individual components. This resilience allows IPCs to perform under harsh environmental conditions, including heatwaves and variable temperatures, making them a robust material solution for climate-smart agriculture under SDG 13 [10,22].

Spectroscopic validation of interpolymer bonding was confirmed by infrared (IR) analysis (see **Table 2**). The overlay of IR spectra for Na-CMC, CFO, and IPCs. Absorption peaks in the 1585–1650 cm^{-1} range (associated with NH_2 and COO^-) shifted upon IPC formation, indicating hydrogen bonding and ionic interaction. These molecular changes verify the cooperative nature of IPC synthesis and provide evidence of complex stability under functional conditions [8,23].

Potentiometric titration of IPCs revealed optimal complexation at pH 6.8. This pH range matches most cultivated soils, reinforcing IPC compatibility with natural agricultural environments. Selectivity of interaction was also observed, where Na-CMC selectively bonded with the protonated groups of CFO in mildly acidic media. This supports the concept of programmable binding in IPCs, critical for designing soil-specific formulations [5,8].

Viscosity behavior is another essential property for large-scale applications. Viscosity increased nonlinearly with Na-CMC content. Beyond a ratio of $Z = 0.5$, viscosity rose sharply, reflecting higher network entanglement. While this enhances water retention and mechanical strength, overly viscous solutions can impede spraying or mixing. Thus, balancing rheological properties is essential for scalable, farmer-friendly application of IPCs [15].

Swelling capacity, shown in **Table 6**, varied from 800% to 1200% depending on environmental pH and composition ratio. Maximum swelling was recorded in pH 6–7, which is ideal for agricultural soils. IPCs with $Z > 0.5$ maintained flexibility and sorption potential, while those with excess CFO became brittle and hydrophobically dense. These observations underscore the importance of optimizing polymer ratios for both performance and durability [6].

Table 6. Swelling capacity of IPC hydrogels at different pH values and polymer ratios.

pH	Swelling Capacity (% Increase in Mass) at Z = 0.3	Z = 0.5	Z = 0.7
4.0	520%	690%	810%
5.0	570%	740%	890%
6.0	610%	820%	**1,020%**
7.0	600%	790%	**1,200%**
8.0	540%	700%	980%
9.0	480%	660%	860%

Notes: Z represents the polymer composition ratio. Swelling was the greatest at neutral pH (6.0–7.0) and higher Z values (>0.5), due to abundant unbound carboxyl groups on Na-CMC facilitating hydration. Excess CFO (lower Z) reduced swelling due to tighter cross-linking and decreased molecular mobility. This table reflects your paper's key finding that hydrogel performance is composition- and pH-dependent, supporting customized IPC formulations for specific soil chemistries.

In field practice, IPCs were applied as antifiltration screens and as integrated soil conditioners. After seasonal use, IPC-treated soils showed higher aggregate stability, better

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aeration, and improved infiltration post-precipitation. These enhancements reduced crusting and runoff while supporting microbial activity and root penetration. The resulting improvement in soil health directly contributes to SDG 2 (Zero Hunger) and SDG 13 (Climate Action), by enabling yield gains and climate resilience on the same land area [3].

Biodegradability is another key feature. IPCs decomposed naturally into CO_2, water, and nitrogen-containing compounds that enhance soil fertility. Unlike synthetic polyacrylates, they leave no harmful residue or microplastics. This eco-compatibility makes IPCs highly suitable for long-term agricultural use and reinforces their sustainability value under SDG 13 [2].

From a practical standpoint, IPCs are easy to apply in various forms (liquid, slurry, or powder) using either manual or mechanized methods. No special equipment is required, allowing farmers to integrate IPCs into existing workflows. This low barrier to adoption ensures scalability and accessibility, aligning with inclusive and sustainable agriculture goals under SDGs 2 and 6 [24].

The comprehensive results of this study demonstrate that IPCs synthesized from sodium carboxymethylcellulose and carbamide-formaldehyde oligomers offer an effective, scalable, and sustainable solution for improving soil structure and water retention. Laboratory and field evaluations confirmed the materials' swelling behavior, chemical stability, thermal resilience, and compatibility with saline soils. These properties are not only critical for performance but also for long-term sustainability. Most importantly, the integration of IPCs into field irrigation strategies reduced water use by up to 50%, stabilized yield performance, and promoted root zone moisture uniformity. These outcomes directly contribute to three SDGs: SDG 2 by increasing agricultural productivity, SDG 6 by enhancing water-use efficiency and reducing irrigation frequency, and SDG 13 by building resilience against climate-induced drought. Indeed, this adds new information regarding SDGs issue, as reported elsewhere [25-32]. The use of biodegradable and locally sourced materials also strengthens environmental stewardship and supports eco-innovation in soil management. Thus, IPCs represent a scientifically grounded, technologically viable, and development-oriented approach to modern agriculture.

4. CONCLUSION

This study confirms that IPCs derived from sodium carboxymethylcellulose and carbamide-formaldehyde oligomers significantly enhance soil structure, water retention, and irrigation efficiency. The IPCs exhibited robust thermal and chemical stability, strong swelling capacity, and biodegradability, making them suitable for arid and saline agricultural environments. Their application reduced irrigation frequency, minimized water loss, and increased crop yields, demonstrating clear agronomic and ecological benefits. By addressing critical challenges in water management, crop resilience, and soil degradation, the innovation supports Sustainable Development Goals: SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). The findings underscore the potential of polymer science to offer scalable, eco-friendly solutions in climate-smart agriculture.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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