Chitosan and Alginate Based Conductive Gels for Electroencephalography: Comparative In Vitro Characterization of Fifteen Formulations

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Abstract

Electroencephalography (EEG) relies on conductive gels for effective electrode–skin contact, but conventional gels dehydrate, leave residue, and are not biodegradable. This study developed marine-derived gels from chitosan, sodium alginate, and chitosan–alginate hybrids, with selected formulations reinforced with montmorillonite. Of 35 formulations, 15 homogeneous gels were characterized for physicochemical and electrical properties. Gel-only impedance decreased from 85–230 kΩ at ~20 Hz to 21–80 kΩ at 1 kHz, with phase angles shifting toward increasingly resistive behavior. ALG-6*, a montmorillonite-containing alginate gel, combined the highest viscosity, lowest contact angle, and favorable interfacial impedance, and was provisionally prioritized pending biocompatibility and EEG signal-quality testing.



Figure 1. representative sources of sodium alginate and chitosan

Introduction

Electroencephalography (EEG) requires a stable electrode–skin interface for reliable signal acquisition. Conventional gels reduce contact impedance but are synthetic, prone to drying, difficult to remove, and non-biodegradable. Marine-derived chitosan and alginate offer sustainable alternatives, with hybrid blends and montmorillonite reinforcement further tuning viscosity, wettability, and interfacial response. Yet few studies compare these families as EEG couplants at a skin-like interface, where behavior differs from bulk response. This study screened them in gel-only and artificial-skin configurations.

Objectives

- Formulate and macroscopically screen thirty-five gel compositions based on chitosan, alginate, and chitosan–alginate blends, with and without montmorillonite.
- Evaluate physicochemical properties of the fifteen retained gels: apparent viscosity, pH, and apparent contact angle.
- Characterize their electrical behavior through impedance magnitude, phase angle, and derived conductivity across 20 Hz–20 MHz.
- Compare gel-only and SBF-I-conditioned artificial-skin configurations to prioritize candidates for EEG development.

Methodology

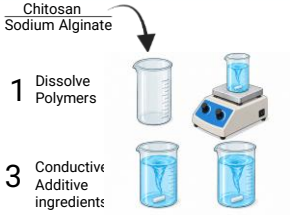


Figure 2. Hydrogel strategy



Figure 3. Characterization Methods

Experimental Results

Table 1. of Physical Properties

Formulation	Viscosity (cP)	pH	Contact angle (°), mean ± SD, n = 10
ALG-1	22,430	5.91	107.91 ± 0.13
ALG-2*	13,130	4.28	89.80 ± 0.05
ALG-4	29,120	5.72	101.61 ± 0.14
ALG-6*	35,310	4.98	61.96 ± 0.23
CHI-2*	31,840	4.33	95.00 ± 0.00
CHI-4	21,430	4.36	97.73 ± 0.59
CHI-7	9,168	4.58	88.44 ± 0.05
CHIALG-1	21,680	4.00	89.35 ± 0.07
CHIALG-2	24,780	4.34	99.22 ± 0.06
CHIALG-3	25,150	4.16	70.18 ± 0.04
CHIALG-4	33,580	7.02	79.21 ± 0.31
CHIALG-6	26,140	7.07	99.80 ± 0.12
CHIALG-9*	29,980	4.08	82.47 ± 0.24
CHIALG-11*	28,120	4.12	97.37 ± 0.16
CHIALG-12*	23,910	3.95	97.57 ± 0.05

An asterisk denotes a montmorillonite-containing formulation.

Table 2. Electrochemical Properties

Formulation	|Z| 20 Hz (kΩ)	|Z| 1 kHz (kΩ)	φ 20 Hz (°)	φ 1 kHz (°)
ALG-1	210	38	−48	−10
ALG-2*	210	38	−48	−10
ALG-4	230	40	−51	−21
ALG-6*	157	38	−48	−12
CHI-2*	120	25	−52	−7
CHI-4	167	62	−38	−3
CHI-7	150	80	−31	0
CHIALG-1	105	43–44	−52	−10
CHIALG-2	115	45	−45	−12
CHIALG-3	99	36	−47	−8
CHIALG-4	153	21	−55	−10
CHIALG-6	99	31	−55	−12
CHIALG-9*	99	38	−42	0
CHIALG-11*	108	40	−50	−3
CHIALG-12*	85	34	−38	−2

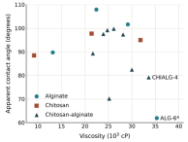


Figure 4. Apparent contact angle as a function of viscosity for the selected formulations.

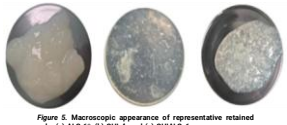


Figure 5. Macroscopic appearance of representative retained gels: (a) ALG 6, (b) CHI-4, and (c) CHIALG-6.*

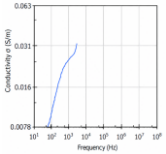


Figure 6 Conductivity of ALG-6 as a function of frequency.*

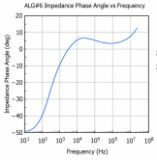


Figure 7. Impedance phase angle of ALG-6 as a function of frequency.*

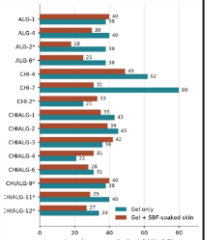


Figure 9. Impedance magnitude at 1 kHz for gel-only and gel + SBF-conditioned artificial skin configurations.

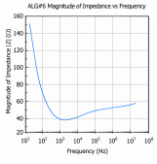


Figure 8. Impedance magnitude of ALG-6 as a function of frequency.*

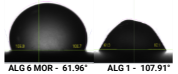


Figure 10. Representative contact-angle measurements for ALG-6 and ALG-1.*

Analysis and Results

Fifteen homogeneous gels were characterized. Apparent viscosity ranged from 9,168–35,310 cP, pH from 3.95–7.07, and contact angle from 61.96°–107.91°. Montmorillonite-containing formulations showed higher viscosity, and ALG-6* combined the highest viscosity with the lowest contact angle, indicating favorable consistency and spreading. Gel-only impedance fell from 85–230 kΩ at ~20 Hz to 21–80 kΩ at 1 kHz, with phase angles shifting toward resistive ionic behavior. The artificial-skin interface substantially reordered rankings: at 1 kHz, ALG-2* was lowest (18 kΩ, pending verification), followed by ALG-6* (25 kΩ). Balancing viscosity, wettability, pH, and impedance, ALG-6* was provisionally prioritized.

Conclusion

The biopolymer-based gels showed robust, consistent, and highly relevant physicochemical and electrical properties pertinent to EEG applications. ALG-6* was provisionally prioritized for its best overall balance of viscosity, wettability, pH, and impedance, while ALG-2* recorded the lowest interfacial impedance at 1 kHz, pending verification. The artificial-skin interface substantially altered the electrical response, underscoring the need for substrate-aware testing. Values approach those reported for EEG couplants, but the comparison is indirect because published data are in vivo on the scalp.

Recommendation/Future Work

- Replicate the prioritized formulations across independent batches and re-acquire the flagged impedance spectra.
- Evaluate the prioritized gels on real skin to better approximate the EEG electrode–skin interface.
- Measure the SBF-I-conditioned artificial skin without gel to establish a baseline separating substrate from gel contribution.
- Develop an optimized formulation combining the most favorable characteristics of ALG-6*, CHIALG-12*, and CHI-2*. Validate signal quality and biocompatibility for clinical use.

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