Evaluation of Plasma Induced Surface Modification in PLA- Aliginate Biocomposites and their Dielectric Response: A Review of Literature

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2026

ABSTRACT

Surface engineering plays an important role in improving the performance of biomaterials used in tissue engineering. Polylactic acid (PLA)–alginate biocomposites combine the mechanical strength of PLA with the hydrophilic and bioactive properties of alginate; however, their surface characteristics can limit early cellular interactions. This literature review (2010–2025) examines how non-thermal plasma (NTP) surface modification affects the physicochemical and dielectric behavior of PLA–alginate biomaterials. Plasma treatment introduces polar functional groups that increase surface energy and enhance wettability. As a result, dielectric properties such as permittivity and AC conductivity increase, indicating greater interfacial polarization and hydration within the material. These changes promote improved protein adsorption and fibroblast adhesion, supporting better biological compatibility. The findings emphasize the importance of plasma-induced surface functionalization for optimizing PLA-based scaffolds in tissue engineering and regenerative medicine.

INTRODUCTION

The growing demand for effective damage tissue treatments and organ failure donors has driven the development of biomaterials to prioritize the patient's health and ensure safety. Researching biocompatible and biodegradable polymers natural and synthetic, has emerged a vital area for biomedical, tissue engineering and environmental sustainability. Focusing on evolving, replacing and restoring the function of human tissue and damaged or lost organs. Polylactic acid (PLA), is widely used due to its biodegradability, biocompatibility and mechanical stability. Unfortunately, the PLA applications are limited due to several disadvantages such as, excessive brittleness, poor osteointegration, low cell adhesion, and biological inertness, in fact depends on the PLA applications, it has a low degradation rate. To avoid disadvantages, PLA is combined with other polymers or agents. In addition, the combination of PLA and natural polymer as alginate, providing a highly beneficial increase in surface wettability and hydrophilicity promoting cell adhesion and biocompatibility. For high moisture the absorbance capacity of alginate-chitosan composite is developed to reduce moisture permeability adding antimicrobial benefits improving mechanical properties. Furthermore, surface modification techniques such as non thermal plasma (NTP) treatment has evolved as effective strategies to improve surface chemistry increasing energy, wettability, and biological responses without damaging the properties of the material.

OBJECTIVES

- Review plasma-modified PLA biomaterials (2010-2025).
- Analyze how plasma treatment alters surface chemistry and wettability.
- Examine changes in dielectric properties (ε′, ε″, tanδ, σac).
- Determine how these modifications influence cell adhesion and biological performance.

METHODOLOGY

Selection of Topics	Selection & Refinement of Information	Research and Data Compilation
Structure the research by identifying key properties and physicochemical advancements relevant to the growing field of regenerative medicine and tissue engineering.	**Filter**: articles, reviews and published research papers between 2010-2025	**Gathered information from Databases:** PubMed, MDPI, Scopus, Web of Science, Science Direct and ResearchGate.
Enhance the objectives and analysis of results leading to structured information analysis highlighting it's relevance to tissue engineering applications and future advances.	**Prioritize** sources based on relevance and **organize** references using a bibliographic manager Mendeley.	**Used research criteria based on keywords:** polylactic acid, alginate, non-thermal plasma, dielectric spectroscopy, tissue engineering, biomaterials

DATA

TABLE I Summary of Plasma Types, Dielectric Effects, and Biological Responses Reported in Included Studies

Plasma type	Key parameters	Dielectric effects	Biological response
Dielectric barrier discharge (DBD)	Atmospheric pressure; AC high voltage (kV); air, O_2, N_2 or Ar; short exposure times	Increase in ε′ and tan δ at low frequencies; enhanced Maxwell–Wagner–Sillars polarization due to a hydrated interphase	Enhanced protein adsorption; improved fibroblast and osteoblast adhesion and proliferation
Atmospheric pressure plasma jet (APPJ)	Moderate voltage; controlled gas flow; room-temperature operation	Increase in AC conductivity (σ_ac) and interfacial permittivity due to higher ionic mobility	Improved cell spreading and early cell–material interactions
Low-pressure RF plasma	Vacuum environment; longer treatment times; uniform energy distribution	More homogeneous dielectric response with reduced interfacial variability	Highly reproducible cell adhesion and stable surface activation
Oxidative plasma (O_2/air)	High density of reactive oxygen species	Higher dielectric losses due to increased surface dipole density	Significant improvement in wettability and overall surface bioaffinity

ANALYSIS AND RESULTS

Literature findings show that non-thermal plasma (NTP) treatment improves the surface properties of PLA–alginate biomaterials.

- **Wettability increased:** contact angle reduced (>80° → ~50–70°).
- **Surface functionalization:** addition of –OH, –COOH, and –C=O groups.
- **Dielectric response increased:** higher permittivity (ε′) and AC conductivity (σac).
- **Biological response improved:** greater protein adsorption and fibroblast adhesion.

These trends indicate that plasma modification enhances both dielectric behavior and cellular interaction, supporting the objective of improving PLA-based scaffolds for tissue engineering.

CONCLUSION

This review demonstrates that non-thermal plasma (NTP) surface modification significantly improves the performance of PLA–alginate biomaterials used in tissue engineering. Plasma treatment introduces polar functional groups that increase surface energy and wettability, resulting in improved dielectric properties such as higher permittivity and conductivity. These physicochemical changes enhance protein adsorption, fibroblast adhesion, and overall cellular interaction, indicating improved biological compatibility of the scaffold. These findings support the development of a plasma–surface–dielectric framework that can guide the rational design of next-generation biomaterials for regenerative medicine.

FUTURE WORK

- Integration of 4D bio printing and smart biomaterials.
- Development of gene-activated scaffolds.
- Use of bioelectronic interfaces for tissue monitoring.
- Application of AI-guided biomaterial design.

These advances aim to create adaptive and patient-specific regenerative platforms for tissue engineering.

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