# Alginate–Pea Protein Hydrogels for Encapsulation of Antioxidants from Low-Grade Mulberry Leaf Tea and Their In Vitro pH-Responsive Release Behavior

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**Abstract**

Low-grade mulberry leaf tea residue (LGMLT), a by-product of tea processing, is a potential source of phenolic antioxidants but remains underutilized due to stability limitations. This study aimed to develop alginate–pea protein hydrogel beads as a food-grade encapsulation system for LGMLT extract. The effects of extraction and drying methods on yield (%), total phenolic content (TPC), and antioxidant capacity (ABTS and FRAP assays) of LGMLT extract powder were evaluated. In addition, the physicochemical properties including particle size, encapsulation efficiency (EE) and water-holding capacity (WHC) of LGMLT-loaded hydrogel beads prepared at different alginate-to-LGMLT extract ratios (2:1 and 3:4), as well as their antioxidant activity and pH-responsive release behavior, were evaluated. The results showed that the quality of LGMLT extract powder was influenced by extraction and drying methods, with ultrasonication-assisted extraction followed by freeze drying providing higher phenolic retention and antioxidant capacities, while spray drying yielded greater powder recovery. Hydrogel properties were strongly affected by the alginate-to-LGMLT extract ratio; higher alginate levels improved bead uniformity, EE, and WHC, whereas increased extract loading enhanced phenolic content and antioxidant activities. In vitro release studies under simulated pH conditions showed rapid phenolic release at pH 1.2 and a more sustained release at pH 7.4, indicating the pH-responsive behavior of the hydrogel matrix. Differences observed between ABTS and FRAP assays suggested composition-dependent antioxidant responses. These findings demonstrate the potential of alginate–pea protein hydrogels as a tunable encapsulation approach for stabilizing plant-derived phenolics and promoting the value-added utilization of tea-processing residues.

***Keywords*****:** *alginate–pea protein hydrogel, encapsulation efficiency, plant extract encapsulation, mulberry leaf tea residue, phenolic compounds, pH responsive release*