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# Formulating and characterizing bentonite-intercalated and polymer-modified urea composites for controlled nutrient release

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Conventional urea fertilizers exhibit critically low nitrogen use efficiency attributable to rapid aqueous dissolution, resulting in substantial urea losses. Contemporary controlled-release fertilizer technologies face significant constraints, including prohibitive manufacturing costs, environmental persistence of synthetic polymer coatings, and limited scalability, challenges particularly severe in dry tropical soils with low water retention. This study developed a controlled-release formulation employing molecule intercalation and polymer modification to achieve sustained urea release through a synergistic dual barrier mechanism. Bentonite-urea composites (50:50) were prepared through mechanical homogenization, with polyvinyl alcohol (PVA) incorporated at systematically varied concentrations (1%, 3%, and 5%) as a binder. XRD analysis confirmed successful urea intercalation, evidenced by $d_{001}$ basal spacing expansion from 14.84 Å to 18.59 Å, indicating urea molecule insertion between the bentonite interlayers. FTIR analysis confirmed the presence of characteristic functional groups of both urea and bentonite in the composite. The observed reduction in O–H stretching intensity suggested weak hydrogen-bonding interactions between urea and bentonite. SEM analysis showed that the final composite (urea–bentonite with 5% PVA) displayed a more compact, smoother, and partially agglomerated surface, indicating successful urea incorporation and the formation of a PVA polymer network that covers the clay layers, fills void spaces, and reduces surface porosity. Bentonite intercalation extended the urea release duration to 6 hours ($R^2 = 0.96$). Furthermore, polyvinyl alcohol (PVA) modification exhibited a concentration-dependent retardation effect, increasing the release duration to 24 hours at 1% PVA, 48 hours at 3% PVA, and 72 hours at 5% PVA. The optimized 5% PVA formulation demonstrated anomalous transport behavior (n=0.59), indicative of coupled Fickian diffusion and polymer relaxation, achieving an 81% reduction in release rate constant. These findings demonstrate that bentonite-PVA dual barrier systems achieve controlled urea release, although comprehensive field validation and techno-economic assessment are necessary for practical implementation.

**Keywords:**

Controlled-release fertilizer, nitrogen efficiency, urea, bentonite, polyvinyl alcohol