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## D<sup>2</sup>mcd: A modular dual-term diffusion framework for coffee drying

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### Abstract

Accurate prediction of moisture transport during coffee drying remains essential for process optimisation, energy efficiency, and quality preservation. Traditional thin-layer models frequently rely on empirical fitting or assume constant effective diffusivity, thereby limiting mechanistic interpretability and predictive reliability under transient thermal conditions. This work presents the development and experimental validation of the D<sup>2</sup>MCD (Dual-Mode Moisture Coupled Diffusion) family, a modular diffusion-based framework derived from a truncated spherical Fickian solution and extended through a time-stretch integral formulation. The model expresses the moisture ratio in a compact dual-term structure in which effective diffusivity evolves dynamically with temperature and moisture content. Temperature dependence is incorporated through an Arrhenius relationship, while moisture dependence is represented using a power-law term. This formulation enables the representation of environmental transients within a unified mathematical structure. Four model variants were evaluated: D<sup>2</sup>MCD-Core, D<sup>2</sup>MCD-Iso, D<sup>2</sup>MCD-XR (accounting for reabsorption effects), and D<sup>3</sup>MCD-T (including thermo-diffusive coupling). Experimental drying tests were conducted on *Coffea arabica* L. var. Cenicafé 1 between 35 and 50 °C under controlled airflow and psychrometric conditions representative of mechanical coffee drying systems. All model variants reproduced the characteristic two-stage drying behaviour with high accuracy ( $R^2 > 0.99$ ). The estimated effective diffusivities followed consistent Arrhenius behaviour, yielding activation energies of approximately 34 kJ mol<sup>-1</sup>, in agreement with reported values for hygroscopic agricultural materials. The modular architecture of the D<sup>2</sup>MCD framework enables hierarchical model selection depending on drying complexity, ranging from near-isothermal conditions to fully coupled thermo-diffusive environments. By combining mechanistic consistency with numerical compactness, the proposed approach provides a robust foundation for model-based dryer design, process control, and predictive simulation in coffee postharvest engineering.

**Keywords:** Arrhenius kinetics, Effective diffusivity, Moisture transport, Postharvest engineering, Spherical geometry, Thermo-diffusive coupling, Time-stretch integral