Numerical simulation of textile dyeing with purple onion peel pigments: key phenomena and parametric analysis

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Background & Aim: Environmental concerns surrounding synthetic dyes have intensified the search for sustainable alternatives in the textile industry [1]. In this context, natural dyes from renewable sources stand out as a safer environmental alternative to conventional dyeing processes, which consume large amounts of water and release toxic compounds. Thus, studying natural dyeing is essential, and modeling helps reduce costs and materials while enabling the analysis of extreme cases. However, textile dyeing models are limited and mainly focus on chemical [2] dyes or effluent treatment [3]. This study presents a new mathematical model to simulate wool and cotton dyeing with pigments from purple onion skins (natural dye), considering dye diffusion and sorption/desorption in textile fibers. **Methods:** A one-dimensional numerical approach was adopted, combined with volumetric average calculation techniques, to analyze mass transfer through the textile sample thickness and predict the temporal evolution of dye concentration. **Results:** Strong agreement was obtained between the numerical and analytical results (qualitative tendencies), confirming the correct implementation of the mathematical approach. Parametric studies were conducted to explore the main influences on the dyeing process. The results revealed the following: i) increasing fabric thickness results in surface dye accumulation, hindering penetration; ii) increasing the solid fraction fivefold and fiber density sixfold reduces liquid-phase dye concentration by 1.4 and 1.7 times, respectively; iii) decreasing the diffusion coefficient 100-fold prevented dye penetration after 600 s and iv) increasing the convective coefficient and mass concentration in dyeing solution enhanced dye uptake by the textile. **Conclusions:** Further quantitative validation (e.g., using dye concentration data) is required; however, the developed model provides a basis for predicting and optimizing dye–fiber interactions.

Keywords: Textile dyeing; natural dye; numerical simulation; dye diffusion in water; dye sorption in fibers

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