SISTEM PREDIKSI PROTEIN TANAMAN *MICROGREENS* DENGAN REPRESENTASI KLOROFIL BERBASIS *MACHINE LEARNING* MENGGUNAKAN *HYPERSPECTRAL IMAGING* PADA *PLANT FACTORY*

INTISARI

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Microgreens brokoli merupakan pangan fungsional bernilai tinggi yang kandungan proteinnya perlu dipantau secara efisien selama budidaya di *plant factory*. Penelitian ini bertujuan mengembangkan sistem prediksi kandungan protein *microgreens* brokoli secara nondestruktif dengan mengintegrasikan pencitraan hiperspektral, parameter fisiologis tanaman, dan algoritma *machine learning*. Akuisisi citra dilakukan menggunakan kamera hiperspektral Specim IQ pada rentang 452-899 nm (151 pita spektral) terhadap 26 sampel *microgreens* brokoli yang diberi perlakuan biofertilizer mikroalga. Kandungan protein kasar diukur secara destruktif melalui metode Kjeldahl sebagai data referensi. Dua pendekatan pemodelan dibandingkan, yaitu pendekatan spektrum penuh dan pendekatan berbasis indeks vegetasi yang memanfaatkan pengetahuan domain. Enam algoritma regresi diuji, meliputi Ridge, Lasso, ElasticNet, PLSR, SVR, dan Random Forest. Hasil penelitian menunjukkan bahwa model ElasticNet berbasis indeks dengan enam fitur *domain knowledge*, yang mencakup indeks vegetasi, parameter fisiologis, dan fitur interaksi spektral-perlakuan, menghasilkan performa terbaik dengan R^2 = 0,7767, RMSE = 0,9562%, dan RPD = 2,1163 (kategori *good*), mengungguli 112 kombinasi spektrum penuh dengan selisih RPD sebesar 0,5576. Validasi tiga lapis melalui LOOCV, bootstrap 500 iterasi, dan Y-randomization 200 iterasi mengonfirmasi stabilitas serta signifikansi statistik model. Penelitian ini mendemonstrasikan bahwa pada kondisi dataset terbatas, pendekatan berbasis pengetahuan domain lebih efektif daripada pendekatan data-driven murni untuk prediksi protein secara nondestruktif di *plant factory*.

Kata kunci: citra hiperspektral, *machine learning*, *microgreens* brokoli, *plant factory*, prediksi protein

MICROGREENS PLANT PROTEIN PREDICTION SYSTEM WITH CHLOROPHYLL REPRESENTATION BASED ON MACHINE LEARNING USING HYPERSPECTRAL IMAGING IN PLANT FACTORY

ABSTRACT

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Broccoli microgreens are high-value functional foods whose protein content requires efficient monitoring during cultivation in a plant factory. This study aimed to develop a non-destructive protein content prediction system for broccoli microgreens by integrating hyperspectral imaging, plant physiological parameters, and machine learning algorithms. Hyperspectral images were acquired using a Specim IQ camera operating within 452–899 nm (151 spectral bands) on 26 broccoli microgreen samples treated with microalgae biofertilizer. Crude protein content was determined destructively via the Kjeldahl method as reference data. Two modeling approaches were compared: a fullband spectral approach and a domain knowledge-driven vegetation index-based approach. Six regression algorithms were evaluated, including Ridge, Lasso, ElasticNet, PLSR, SVR, and Random Forest. The results demonstrated that the ElasticNet index-based model with six domain knowledge features, comprising vegetation indices, a physiological parameter, and spectral-treatment interaction features, achieved the best performance with R^2 = 0.7767, RMSE = 0.9562%, and RPD = 2.1163 (good category), outperforming 112 fullband combinations by an RPD margin of 0.5576. Three-layer validation through LOOCV, 500-iteration bootstrap, and 200-iteration Y-randomization confirmed the model's stability and statistical significance. This study demonstrates that under limited dataset conditions, a domain knowledge-driven approach is more effective than a purely data-driven approach for non-destructive protein prediction in a plant factory setting.

Keywords: broccoli microgreens, hyperspectral imaging, machine learning, plant factory, protein prediction