ANALISIS VARIABILITAS IKLIM, INTEGRASI SISTEM PERTANIAN PRESISI, DAN PEMODELAN MACHINE LEARNING UNTUK PREDIKSI EMISI GAS RUMAH KACA PADA BUDIDAYA CABAI

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ABSTRAK

Perubahan iklim dan intensifikasi praktik budidaya hortikultura menimbulkan tantangan serius terhadap keberlanjutan sistem pertanian, khususnya pada komoditas cabai yang sensitif terhadap variabilitas iklim dan pengelolaan lahan. Penelitian ini bertujuan untuk menganalisis variabilitas dan tren perubahan iklim di Kabupaten Sleman; menginventarisasi serta mengevaluasi fluks gas rumah kaca (GRK), khususnya metana (CH_4) dan dinitrogen oksida (N_2O), kombinasi praktik pemupukan dan mulsa; menganalisis hubungan antara variabel iklim mikro, sifat tanah, dan fluks GRK; menetapkan ambang batas intensitas emisi GRK sebagai indikator efisiensi emisi; dan pengembangan model prediksi emisi GRK berbasis Machine Learning (ML) dan pendekatan pertanian presisi. Analisis iklim dilakukan menggunakan data curah hujan periode 1981–2020 dengan uji *Mann–Kendall*, *Sen's slope*, dan klasifikasi agroklimat metode Oldeman serta Schmidt–Ferguson. Inventarisasi emisi GRK dilakukan melalui percobaan lapang budidaya cabai dengan Rancangan Acak Kelompok (RAK), tiga ulangan, dan kombinasi perlakuan pupuk serta mulsa di dua lokasi penelitian, Pakem dan Mlati, pada musim tanam ketiga (MT III) tahun 2024. Pengukuran fluks CH_4 dan N_2O menggunakan metode *closed chamber*, dengan data iklim mikro dan tanah diperoleh dari *Automatic Weather Station* (AWS) dan *Soil Monitoring System* (SMS). Pemodelan emisi GRK dikembangkan menggunakan *Adaptive Neuro-Fuzzy Inference System* (ANFIS) dan *Support Vector Regression* (SVR) dengan skema pembagian data 70% untuk pelatihan dan 30% untuk pengujian serta five-fold cross-validation. Hasil analisis menunjukkan pergeseran tipe agroklimat dari C3/D3 menuju B3/D3 (menjadi lebih basah dari sebelumnya) disertai tren peningkatan curah hujan yang signifikan sebesar $0,52 \pm 0,08$ mm tahun^{-1}, berimplikasi pada penyesuaian kalender tanam cabai. Hasil percobaan lapang mengindikasikan bahwa kombinasi perlakuan P0M2 (tanpa pupuk kimia dengan penggunaan mulsa) memberikan keseimbangan terbaik antara produktivitas (168,9 dan 122,7 kuintal·ha^{-1}) dan emisi rendah. Variabel iklim mikro, khususnya suhu dan kelembapan udara serta curah hujan, berperan dominan dalam mengendalikan fluks CH_4, sedangkan kelembapan tanah, nitrogen, dan pH tanah menjadi faktor utama pengendali fluks N_2O. Ambang intensitas emisi GRK (Greenhouse Gas Intensity, GHGI) ditetapkan sebesar 437,42 kg $CO_2e \cdot ton^{-1}$ yang dapat digunakan sebagai kriteria kuantitatif untuk menilai efisiensi dan kelayakan karbon praktik budidaya cabai di tingkat petani. Dari sisi pemodelan, ANFIS menunjukkan kinerja terbaik ($R^2 = 0,56$) dalam memprediksi fluks CH_4 dan N_2O karena mampu mendekteksi pada data non-linear dan berfluktuasi tinggi. Secara keseluruhan, penelitian ini menyimpulkan bahwa praktik budidaya cabai berbasis P0M2 merupakan pendekatan *low input–low emission* yang bisa diterapkan sebagai strategi adaptasi dan mitigasi perubahan iklim pada sistem pertanian cabai di Indonesia.

Kata kunci: Variabilitas iklim; Cabai; Emisi GRK; Iklim Mikro; Atribut tanah; *Greenhouse Gas Intensity* (GHGI); *Machine Learning*

CLIMATE VARIABILITY ANALYSIS, INTEGRATION OF PRECISION AGRICULTURE SYSTEMS, AND MACHINE LEARNING MODELLING FOR PREDICTING GREENHOUSE GAS EMISSIONS IN CHILLI CULTIVATION

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ABSTRACT

Climate change and the intensification of horticultural farming practices pose serious challenges to the sustainability of agricultural systems, particularly for chili cultivation, which is highly sensitive to climate variability and land management practices. This study aims to analyze climate variability and trends in Sleman Regency; to inventory and evaluate greenhouse gas (GHG) fluxes, particularly methane (CH_4) and nitrous oxide (N_2O), under different fertilizer and mulch management combinations; to examine the relationships between microclimatic variables, soil properties, and GHG fluxes; to determine threshold values of GHG emission intensity as indicators of emission efficiency; and to develop predictive models of GHG emissions based on machine learning (ML) within a precision agriculture framework. Climate analysis was conducted using rainfall data for the period 1981–2020, applying the Mann–Kendall test, Sen's slope estimator, and agroclimatic classification based on the Oldeman and Schmidt–Ferguson methods. GHG emission inventory was carried out through field experiments on chili cultivation using a randomized block design with three replications and combinations of fertilizer and mulch treatments at two study sites, Pakem and Mlati, during the third planting season (MT III) of 2024. CH_4 and N_2O fluxes were measured using the closed-chamber method, while microclimate and soil data were obtained from an Automatic Weather Station (AWS) and a Soil Monitoring System (SMS). GHG emission prediction models were developed using Adaptive Neuro-Fuzzy Inference System (ANFIS) and Support Vector Regression (SVR) with a data split of 70% for training and 30% for testing, combined with five-fold cross-validation. The results indicate a shift in agroclimatic types toward wetter conditions accompanied by a significant increasing trend in annual rainfall of 0.52 ± 0.08 mm year^{-1}, implying the need for adjustments in the chili cropping calendar. Field experiment results show that the P0M2 treatment combination (no chemical fertilizer with mulch application) provides the best balance between productivity (168.9 and 122.7 quintals ha^{-1}) and low GHG emissions. Microclimatic variables, particularly air temperature, relative humidity, and rainfall, play a dominant role in controlling CH_4 fluxes, whereas soil moisture, soil nitrogen content, and soil pH are the main controlling factors for N_2O fluxes. The threshold value of GHG emission intensity (Greenhouse Gas Intensity, GHGI) was determined at 437.42 kg CO_2e ton^{-1}, which can be used as a quantitative criterion to assess carbon efficiency and the feasibility of chili farming practices at the farm level. In terms of modeling performance, ANFIS demonstrated the best performance ($R^2 = 0.56$) in predicting CH_4 and N_2O fluxes due to its ability to capture nonlinear relationships and highly fluctuating data patterns. Overall, this study concludes that the P0M2-based chilli cultivation practice represents a low-input–low-emission approach that can be implemented as a strategic framework for climate change adaptation and mitigation in chilli farming systems in Indonesia.

Keyword : *Climate variability; Chili; Greenhouse gas emissions; Microclimate; Soil attributes; Greenhouse Gas Intensity (GHGI); Machine learning*