Integrated energy-water assessment framework for calcium deficiency control in agricultural greenhouses: A data-driven model predictive control approach

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Abstract

Widespread calcium deficiency in modern agriculture impacts plant health and crop productivity, as seen in cucumber crops with leaf yellowing, revealing broader nutritional implications. Calcium uptake, crucially linked to transpiration-driven water flow, requires thorough temperature and irrigation management. However, rapid water uptake, driven by high transpiration rates in intense sunlight conditions such as the case in hyper-arid regions, can hinder calcium absorption. Top of FormIn response to this challenge, this study presents an innovative approach using data-driven Model Predictive Control (MPC) to manage calcium deficiency in hyper-arid region greenhouses, integrating two MPC systems for optimal irrigation and temperature control. The irrigation control MPC relies on a comprehensive set of input variables, including microclimate data along with hyperspectral imaging data, processing the latter to calculate vegetation indices for analysing different plant characteristics. This system dynamically regulates irrigation to optimise soil moisture levels and enhance subsequent calcium uptake by plants. Concurrently, the temperature control MPC employs a set of input parameters, including solar radiation, external temperature, humidity, fan speed, and HVAC control. By considering these factors, the MPC system effectively controls temperature within the greenhouse, ensuring an optimal microclimate for calcium uptake. This integrated energy-water assessment framework offers a holistic and technologically advanced approach to calcium deficiency control. It leverages cutting-edge data-driven techniques, microclimate sensors, hyperspectral imaging, and advanced control strategies, exemplifying the use of Agriculture 4.0 and precision agriculture, to create an optimised greenhouse environment that enhances calcium uptake in plants. The findings of this study have significant implications for sustainable agriculture, including improved crop health and yields, decreased resource use, and enhanced food security.

**Keywords**: Greenhouse, Calcium Deficiency, Model Predictive Control, Precision Agriculture, Agriculture 4.0.

* 1. Introduction

The use of agricultural greenhouses has become integral for crop cultivation, particularly in regions with unfavourable weather conditions such as hyper-arid regions. Greenhouses offer controlled environments that enhance productivity. However, the inherent challenge of maintaining stable microclimate conditions within these structures often leads to suboptimal crop health (Ghiat et al., 2023a; Mahmood et al., 2020). Unpredictable fluctuations in temperature and inefficient irrigation practices contribute to this issue, creating an environment where the early detection and mitigation of crucial crop stresses and nutritional deficiencies, such as calcium, become challenging (Fahad et al., 2017). Calcium deficiency poses a substantial threat to plant health, influencing nutrient absorption and, consequently, overall crop productivity. Compounding the issue is the difficulty in early detection, as symptoms may manifest late in the growth cycle, hindering timely interventions (Olle and Bender, 2009). Several studies discussed the challenge of calcium deficiency in different plants (Barker and Sonneveld, 1988; Ho and Adams, 1994). Some studies have focused on soil amendment approaches to solve this challenge (Codling and Jaja, 2022). Others have explored advanced irrigation techniques to optimise irrigation water that can ensure a consistent supply of calcium to plants (Kirnak and Demirtas, 2006).

Various control strategies have been employed in agricultural greenhouse environments such as Proportional Integral Derivative (PID), Model Predictive Control (MPC), and fuzzy logic. While the PID method is widely used for its simplicity, it necessitates controller adjustments, resulting in delays. Additionally, it is less adept at handling system disturbances and constraints, assumes linearity in the system, and lacks predictive capabilities. In contrast, MPC can effectively address these limitations, providing a superior control (Mahmood et al., 2021).

This study addresses the challenge of calcium deficiency by proposing an innovative energy-water integrated solution, leveraging advanced data-driven MPC strategies. The goal of this study encompasses understanding fundamental greenhouse operations through the application of data-driven machine learning models capable of discerning intricate relationships among various greenhouse variables. These predictive models are leveraged to evaluate and optimise temperature and irrigation systems. The subsequent step involves integrating these models within a closed-loop MPC framework, employing multi-step tracking and a rolling optimisation to effectively manage temperature and irrigation supply. The ultimate goal is to establish a controlled environment that promotes efficient calcium uptake by the plants through the harmonised interaction of energy and water dynamics.

* 1. System description

This work was conducted within a closed greenhouse in the State of Qatar, characterised by a Venlo-shaped design and predominantly constructed with 4mm tempered glass, covering a net growing area of 715 m2. This controlled environment incorporates a microclimate with CO2 enrichment through propane fed burners inside the greenhouse. Simultaneously, temperature and humidity were regulated by a heating, ventilation, and air conditioning (HVAC) system. The cultivation system within the greenhouse employed hydroponics with coco-peat substrate, specifically for cucumbers.

This work employs a data-driven methodology, emphasising the importance of a substantial dataset in mitigating model bias and overfitting. The data were collected over three crop cycles. For the MPC for temperature control, the measured data include solar radiation, outside and inside temperatures, humidity difference, HVAC control temperature, and ventilation fan speed, with recordings taken at 5-minute intervals. In the case of the MPC for irrigation, the measured data encompasses microclimate parameters such as inside temperature, relative humidity, and CO2 concentration, as well as solar radiation outside the greenhouse, recorded every 5 minutes. Additionally, short-term transpiration rates at the leaf level (measured every 2 s) and daily hyperspectral image-based vegetation indices were recorded for this control. The data collection involved the use of specific equipment for different types of data. Microclimate data were obtained using the Hoogendoorn aspirator box which utilises electronic sensors. Outside weather data were recorded with Hoogendoorn weather station sensors positioned outside the greenhouse. Transpiration rates were measured using a gas exchange measurement system (CIRAS-3, PP systems) based on infrared gas analysers. Hyperspectral images for vegetation indices were captured with a hyperspectral camera operating within the wavelength range of 400-1000 nm (HSC-2, SENOP).

* 1. Methodology

Data-driven models play a pivotal role in simplifying the process of building precise system models by reducing the complexity, cost and the overall effort involved. While few studies have utilised data-driven MPC for greenhouse environment control, the novelty of this work lies in the development of an energy-water framework that integrates data-driven MPC systems. This framework is designed to address calcium deficiency in plants by controlling greenhouse temperature and irrigation water. The aim is to establish an efficient microclimate conducive to optimal calcium uptake by the plants.

The Multi-Layer Perceptron (MLP) is a neural network architecture that operates in a feedforward manner, comprising several layers of interconnected nodes. It uses an activation function to introduce non-linearity and undergoes training through a backpropagation algorithm that iteratively adjusts weights to minimise the errors between predicted and actual outputs (Mahmood et al., 2021). In this work, an MLP model with backpropagation was developed for greenhouse temperature prediction, involving an input layer, a hidden layer with 55 nodes, and an output layer. The predictors integrated into this model encompass fan speed, HVAC control temperature, solar radiation, outside temperature, and humidity difference. The Adam optimiser and the Rectified Linear Unit (Relu) activation function are employed optimising and activating the MLP model, respectively.

The Extreme Gradient Boosting (XGBoost) model, introduced by Chen and Guestrin in 2016, is a scalable implementation of Gradient Boosting machines. This model employs an ensemble approach, combining multiple weak learners to create a robust learner through an additive training process. A key feature of XGBoost lies in its ability to minimise a regularised learning objective to mitigate model complexity and prevent overfitting (Chen and Guestrin, 2016). In this study, the XGBoost model was used to predict short-term transpiration rates. This model integrates input variables consisting of microclimate parameters specifically, greenhouse CO2 concentration, greenhouse relative humidity, greenhouse temperature, and solar radiation. Additionally, it incorporates vegetation indices from hyperspectral images including the normalised difference index (NDVI), the photochemical reflectance index (PRI), and the water band index (WBI). In a prior study, the authors demonstrated that incorporating hyperspectral data enhances the spatial mapping of short-term transpiration prediction. This expansion from a single-point data measurement to a larger sample size significantly improves the model's capability to predict transpiration (Ghiat et al., 2023b).

The datasets for both temperature and transpiration predictions underwent a random split, allocating 20% for model testing and 80% for training. Hyperparameter optimisation was performed for each of the two machine learning models using the GridSearchCV tool, incorporating a five-fold cross-validation. The development of these models was carried out using Python 3.7. **Top of FormTop of Form**

The performance of both predictive models was assessed using two statistical indicators, including the coefficient of determination (R²), representing the proportion of predictable variance, and the root mean square error (RMSE), measuring the average magnitude of differences between predicted and observed values. Eqs. (1) and (2) detail the calculation of these indicators.

$R^{2}=1-\frac{\sum\_{i=1}^{n}\left(Y\_{obs,i}-Y\_{model,i}\right)^{2}}{\sum\_{i=1}^{n}\left(Y\_{obs,i}-\overbar{Y}\_{obs,i}\right)^{2}}$ (1)

$RMSE=\sqrt{\frac{\sum\_{i=1}^{n}\left(Y\_{obs,i}-Y\_{model,i}\right)^{2}}{n}}$ (2)

Moreover, two data-driven MPC systems were implemented using the MLP model for temperature control and the XGboost model for irrigation water control. The MPC algorithm comprises a predictive model, an objective function, and an optimisation algorithm as illustrated in figure 1. The MPC incorporates an optimisation algorithm to identify optimal control values, minimising the sum of squared errors between the reference trajectory or set point (r) and the model-predicted values ($\hat{y}$). The MPC anticipates the future behavior of the plant within a specified prediction horizon (H). Equation 3 outlines the objective function, which is constrained by the temperature control conditions specified in Eq. 4 and the irrigation control conditions detailed in Eq. 5.$ $The irrigation water is constrained by a maximum threshold corresponding to the available water for irrigation Imax. The temperature control is constrained by both the minimum and maximum range of operation for the fan speed and HVAC control temperature represented by umin and umax.

$min J\left(k\right)=\sum\_{i=1}^{H}||r\left(t+i\right)- \hat{y}\left(t+1\right)|\left.​\right|^{2}$ (3)

$0\leq I(t+i)\leq  I\_{max}$ (4)

$u\_{min}<u(t+i)<u\_{max}$ (5)



Figure 1: Model predictive control (MPC) framework.

* 1. Results and Discussion

The implementation of predictive models for temperature and transpiration in the greenhouse, using MLP and the XGBoost, respectively, yielded promising predictive performances. The temperature predictive model, employing MLP, demonstrated a high level of accuracy, with an R2 of 97.8% and an RMSE of 0.340 °C. Similarly, the transpiration predictive model, utilising XGBoost, exhibited a strong performance, achieving an R2 of 97.1% and an RMSE of 0.417 mmol/m²/s.

Fig. 2.a illustrates the performance of the developed MPC system for temperature control over a 2-day period. The MPC model, incorporating the MLP predictive model, closely aligns with the desired temperature, demonstrating its ability to adapt to dynamic conditions. Notably, during the first night when ambient temperatures outside the greenhouse dropped to 12 °C, the MPC system effectively maintained the temperature as desired by manipulating the control variables.

In Fig. 2.b, the MPC system for irrigation control is compared to the actual irrigation system in the greenhouse over a 2-day period (daytime only, as irrigation is stopped before sunset). The existing irrigation system, driven solely by solar radiation variations, lacks the precision offered by the XGBoost model. The XGBoost model, incorporating microclimate parameters, crop health indicators represented by hyperspectral image-based vegetation indices, outperforms the conventional system by considering the complex interplay between these factors. The MPC model for irrigation, designed to maintain optimal soil moisture levels (40%), successfully achieved this goal through a mass balance incorporating transpiration rate and irrigation supply. The model surpassed the existing irrigation system by efficiently managing soil moisture, resulting in lower irrigation requirements. This not only indicates improved water-use efficiency but also points to potential issues with the existing system, which tends to overestimate irrigation needs based on solar radiation variations.

b

a

(a)

(b)

Figure 2: MPC systems for a) temperature and b) irrigation for two days.

The ability of the MPC systems to optimise temperature and irrigation while maintaining optimal soil moisture levels is critical for promoting healthy plant growth and efficient calcium uptake. The observed deficiency in calcium within plants may be attributed to the overestimation of irrigation needs along with unstable temperatures by the existing systems. By leveraging advanced predictive models and MPC, this work demonstrates the potential for enhancing greenhouse control systems and ensuring optimal crop health. The recognition of calcium deficiency's broader impact on nutrient absorption highlights the significance of employing advanced imaging techniques and machine learning methodologies. The incorporation of such technologies not only aids in forecasting optimal greenhouse temperature and water requirements but also serves as a preventive measure against calcium deficiency, contributing to more informed and sustainable approaches to crop management.

* 1. Conclusion

This study presents an energy-water integrated solution to solve calcium deficiency in agricultural greenhouses, particularly in hyper-arid regions. Leveraging advanced data-driven Model Predictive Control (MPC) strategies for irrigation and temperature management within closed greenhouses, the research demonstrates a holistic approach that incorporates microclimate sensing and hyperspectral imaging. The predictive models employed within the MPC systems exhibit high performances, with the temperature model achieving an R2 of 97.8% and an RMSE of 0.340°C, while the transpiration model demonstrates a high R2 of 97.1% and a low RMSE of 0.417 mmol/m²/s. This underscores the accuracy of the models in capturing the complex dynamics of greenhouse microclimate variables, external weather conditions and plant biophysical properties. By dynamically regulating irrigation and optimising the greenhouse microclimate, the proposed framework has the potential to successfully enhance calcium uptake by plants.

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