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## Development of Light-Normalized Crop Monitoring Framework Using RGB-D Imaging and Spatial Light Regression

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### Abstract

To achieve high-quality, high-yield crop production, non-destructive precision monitoring technologies combined with image-based artificial intelligence are being studied to establish finely controlled cultivation environments tailored to crop growth stages. However, variations in lighting-one of the most critical cultivation factors-can cause significant fluctuations in crop image data, limiting the accuracy of phenotype extraction. This study aims to develop a light-normalized crop monitoring framework capable of delivering robust phenotype data under varying light conditions. In a growth chamber equipped with dimmable red, green, and blue LEDs, light intensity and spectral quality were measured across 16 zones at 6 cm vertical intervals. These data were interpolated at 1 cm resolution using 3D spatial regression modeling to generate a continuous light distribution map. Based on response surface analysis, ten lighting conditions were designed at 100, 150, and 200 PPF/D to simulate diverse environments. The target normalization condition was a continuous cool-white LED light, and normalization was performed using the derived spatial model. An RGB-D sensor mounted at LED height captured images, while color calibration targets were randomly placed at various zones and heights to assess normalization performance in both color and depth dimensions. Across 21 lighting scenarios, normalization to the reference environment yielded  $R^2$  values exceeding 0.7, indicating effective correction of lighting-induced variation. This framework provides a foundational approach for developing robust growth monitoring systems for precision lighting feedback control. Future improvements will explore ray tracing and simulation-based techniques to enhance normalization accuracy and computational efficiency under complex greenhouse conditions.

**Keywords:** 3D spatial light regression, lighting condition normalization, non-destructive crop phenotyping, RGB-D monitoring, precision agriculture imaging

## INTRODUCTION

High-quality and high-yield crop production requires precise, stage-specific cultivation recipes, with light serving as a key regulator of plant growth (Bechtold, U et al., 2025). While plant imaging phenotyping enables non-destructive monitoring, varying spectral ratios across developmental stages present challenges for stable assessments. To address this, we developed a light calibration system that provides robust data across ten spectra for response surface methodology-based optimization. Validated with a 24-color calibration board, the system demonstrated strong performance and robustness, highlighting its potential for precise real-time crop phenotyping under dynamic spectral conditions.

## MATERIALS AND METHODS

### Environmental control system and variable light-spectrum configuration

For establishing a variable light-spectrum environment, a plant growth chamber equipped with dimmers for red (R), green (G), and blue (B) light spectra was utilized. Using digital dimmers, the photosynthetic photon flux density (PPFD) of each monochromatic light was quantified at regular intervals across three-dimensional positions (height and spatial distribution). A light distribution map was generated through regression-based interpolation. Based on the computed map, seven spectral compositions for response surface methodology (RSM)-based optimization were established (Yeom et al., 2025), with target PPFD levels of 100, 150, and 200 PPFD. The estimated values were validated by comparing measured PPFD at two arbitrary positions within the chamber using the coefficient of determination ( $R^2$ ), under the following spectral ratios: R:G:B = 1:0:0, 0:1:0, 0:0:1, 1:1:1, 4:1:1, 1:4:1, and 1:1:4. Other environmental conditions were maintained within controlled ranges: temperature 20–24 °C, relative humidity 60–80%, and CO<sub>2</sub> concentration 350–450 ppm.

### Light color calibration under multiple light spectra

Images of a color calibration board placed parallel to the ground at a height of 18 cm were acquired under seven different light spectra using a RealSense D435i depth camera (Intel Corp., Santa Clara, CA, USA). In each acquired image, the region of interest (ROI) corresponding to the board area was selected, and RGB channel values were extracted from each color patch. Since the official reference values of the board are defined in the sRGB color space with gamma characteristics, they were converted into a linear RGB space for preprocessing. Assuming a linear relationship between the extracted values and the reference values, calibration was performed using the least squares method. The performance of the calibration across the seven spectra was evaluated by analyzing the three-dimensional color distribution of each patch, visualizing feature distributions using t-distributed stochastic neighbor embedding (t-SNE), and calculating the coefficient of determination ( $R^2$ ) and Normalized root mean squared metric (NRMSE).

## RESULTS & DISCUSSION

The seven spectral environments established at a height of 18 cm from the computed light distribution map were compared with actual measurements. Across all spectral regions, coefficients of determination ( $R^2$ ) exceeded 0.9, although errors remained at peak wavelengths. This discrepancy may be attributed to the intrinsic characteristics of LEDs, in which photon emission properties vary with temperature and humidity. Furthermore, light distribution maps

generated solely through simple regression were unable to fully capture the uneven distribution of spectra across the entire area. This limitation suggests that future incorporation of optical simulations, such as ray tracing, could enhance the robustness of spatial light-distribution characterization.

In the seven spectral environments, the color patch distributions of the calibration board, as visualized through t-distributed stochastic neighbor embedding (t-SNE), failed to form distinct feature clusters (Fig. 1. A). By contrast, after applying the proposed light calibration, patch features were clearly clustered according to color categories, achieving an average  $R^2$  of 0.7 and a normalized root mean square error (NRMSE) of 0.17 (Fig. 1. B). The application of improved robustness in light distribution mapping through optical simulation is expected to enable stable and reliable light calibration at all three-dimensional positions within the growth chamber.

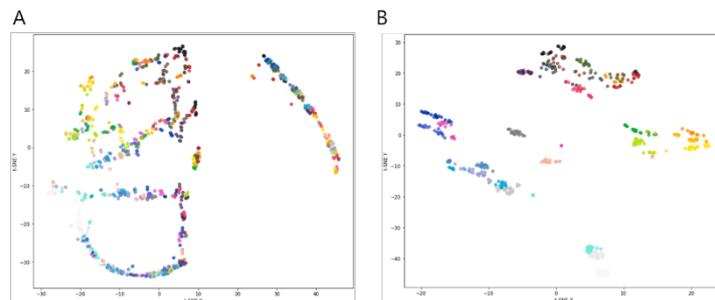


Fig. 1 Light distribution features under seven spectral environments for 24 color patches (A) and feature distributions after light color calibration (B)

## CONCLUSIONS

This study developed a light calibration system for robust plant phenotyping under variable spectral environments in growth chambers. The system achieved high reliability, with coefficients of determination ( $R^2$ ) exceeding 0.9 for light distribution and an average  $R^2$  of 0.7 with an NRMSE of 0.17 for color calibration. While residual errors were observed at peak wavelengths due to the intrinsic properties of LEDs under changing temperature and humidity, the integration of advanced optical simulations such as ray tracing is expected to enhance robustness. These findings demonstrate the potential of the proposed system to enable precise, non-destructive imaging and to support the optimization of spectral light recipes for improved crop production.

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