

The 11th Asian-Australasian Conference on Precision Agriculture (ACPA 11)
October 14-16, 2025, Chiayi, Taiwan

Optimizing Frost Prediction with a Multi-Window CNN–XGBoost Soft-Voting Ensemble

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ABSTRACT

Recent global climate change has increased the frequency of late-spring frost events, causing more severe and widespread damage to orchard growers. Frost formation occurs due to rapid temperature drops over short periods combined with overnight air stagnation; thus, effective prediction requires analyzing patterns across multiple time scales. We introduce a hybrid frost-forecasting framework that combines a multi-window 1-D convolutional neural network (CNN), utilizing 6-, 12-, and 24-hour input windows, with a 24-hour XGBoost model. The system was trained on 97,758 hourly observations collected at the Andong AWS station (South Korea, 2014 – 2025), covering air temperature, relative humidity, wind speed, and soil temperature at 10, 20, and 30 cm depth. Using a soft-voting rule with a decision threshold of 0.70, the ensemble achieved 93.44 % accuracy, an F1-score of 0.85, ROC-AUC 0.967 on an independent 2024 test set, statistically outperforming both stand-alone XGBoost (accuracy = 0.873) and the single-window CNN (accuracy = 0.903). The recall for the frost class—the minority category in our dataset—improved to 0.86, while the number of false negatives – critical for timely grower decision-making – decreased by 11 %. By simultaneously integrating 6-, 12-, and 24-hour windows, the proposed ensemble captures both rapid evening cold surges and slower overnight cooling trends, thereby delivering more balanced and robust predictions than any single-scale model.

Keywords: Frost forecasting, Multi-scale CNN·XGBoost, Soft voting, Smart farming, A.I.

INTRODUCTION

Recent global climate change has made frost damage an increasingly critical threat in open-field environments. To mitigate this risk, AI-based research has focused on improving forecasting accuracy to reduce crop losses. AI-based models need to capture both the relationships among weather variables and their changes over time, while also providing reliable detection of rare frost events. In this study, we propose a forecasting algorithm that combines XGBoost, effective for pattern interpretation, with convolutional neural networks (CNNs), which are well suited for time-series learning. This hybrid approach integrates multiple time scales to improve the accuracy of frost prediction. This is particularly important because frost formation involves both rapid short-term cooling and gradual overnight declines; thus, employing multi-window time series inputs is a key strategy for achieving accurate prediction.

MATERIALS AND METHODS

This algorithm was trained on 97,758 hourly observations collected from the Andong AWS station (South Korea, 2014–2025), including air temperature, relative humidity, wind speed, and soil temperature at depths of 10, 20, and 30 cm, to develop a frost-forecasting framework. The proposed solution integrates a multi-window 1-D convolutional neural network (CNN) with 6-, 12-, and 24-hour inputs and a 24-hour XGBoost model. Final predictions were obtained using a soft-voting scheme

$$P_{ensemble} = \omega P_{XGB} + (1 - \omega) P_{CNN} \quad (1)$$

with a decision threshold of 0.70. Model performance was evaluated on an independent 2024 test set using accuracy, precision, recall and F1-score.

RESULTS & DISCUSSION

The Ensemble_{*opt} algorithm, trained with multi-window inputs of 6, 12, and 24 hours, achieved the best performance (accuracy 0.93, F1-score 0.85). This demonstrates that integrating multiple temporal scales enables the model to capture both rapid cooling surges and gradual overnight declines, effectively learning the diverse patterns of frost events.

Table 1 Classification Report.

| Model | Accuracy | Precision | Recall | F1-score |
|--------------------------|----------|-----------|--------|----------|
| XGB _{Lag6} | 0.87 | 0.69 | 0.76 | 0.72 |
| XGB _{Lag12} | 0.89 | 0.76 | 0.77 | 0.76 |
| XGB _{Lag24} | 0.91 | 0.83 | 0.75 | 0.79 |
| CNN | 0.90 | 0.77 | 0.83 | 0.80 |
| Ensemble _{*opt} | 0.93 | 0.86 | 0.86 | 0.85 |

CONCLUSIONS

By simultaneously integrating 6-, 12-, and 24-hour windows, the proposed ensemble captures both rapid evening cold surges and slower overnight cooling trends, thereby delivering more balanced and robust predictions than any single-scale model. Future work will broaden the training dataset to cover diverse agro-climatic regions, incorporate routinely recorded variables such as solar radiation and rainfall, and deploy the system as a fully operational alert service for orchard growers.

ACKNOWLEDGEMENTS

This work was carried out with the support of the project “Development of Agricultural Big Data Utilization Models and Artificial Intelligence” (Project No. RS-2024-00398963), Rural Development Administration, Republic of Korea, and by a grant from the Gyeongsangbuk-do Provincial Government.

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