From Climate Variability to Digital Twins:

Building Resilience in Sri Lanka's Coconut Supply Chain

Introduction and Background

Coconuts (Cocos nucifera), are the second largest crop in Sri Lanka, cultivated across 4.4 million hectares, contributing around 0.9% of national GDP [1]. As a multipurpose crop, it generated significant economic wealth, with Sri Lanka ranking as the fourth largest exporter of coconut products. National production ranges from 2,500 to 3,000 million nuts annually, with significant monthly fluctuations [1]. Despite this substantial production capacity, coconut yield remains below their potential capacity and unmeet the demand due to different risk factors. Agricultural supply chain, including coconut cultivation, is impacted by five primary types of risks: production risk, market risk, institutional risk, personal risk, and financial risk [2]. Recent studies highlight production risk as the most significant, given its cascading impact on downstream supply chain processes and its potential to amplify other risk types.

Production risk affects the unpredictability of natural growth processes of crops influenced by weather and climate, pests and diseases, and soil conditions [3]. In tropical countries like Sri Lanka, weather and temperature conditions are crucial determinants of crop productivity [4]. The study focuses on the 'Coconut Triangle' districts (Kurunegala, Puttalam, and Gampaha) that significantly contribute (51.8%) to national yield for research with span of three primary agro-climatic zones: dry, intermediate, and wet. Understanding how climate variations affect coconut yield and predictive yield in these regions is essential for developing proactive risk management strategies.

Coconut has emerged as a trending commodity in recent years due to pronounced price volatility in both local and global markets, attracting renewed research interest in the sector. Concurrently, the agricultural research community is increasingly focused on building resilience within supply chains through the adoption of emerging technologies. Given these imperatives, this study aims to analyze the impact of climatic variations on coconut yield in Sri Lanka's major producing districts and identify critical weather parameters to inform the development of a Digital Twin-enabled resilience framework for the coconut supply chain.

Methodology and Data Approach

The maturation of coconut nuts is a prolonged process, influenced by weather circumstances at various phases across different varieties, which may result in yield fluctuations. The climatic conditions three months before and after inflorescence opening influence the quality of button nuts, pollen, pollination process and nut setting. To capture the weather effect for across physiological phase of nuts developing, incorporated lagged climate variable from 8 -13 months prior period to harvest.

The analysis evaluated six primary weather variables: temperature, apparent temperature, duration of daylight, duration of sunlight, precipitation, wind speed, and evapotranspiration with lag features. Machine learning (ML) methodology was employed to investigate non-linear relationships between these climatic factors and coconut yield at the district level. This approach enabled the identification of the most influential weather parameters for each district while capturing the complex, multi-stage interactions between climatic conditions and coconut crop development.

Climatic Drivers of Yield Variability

The relationship between weather variables and coconut yield varies across the three districts, reflecting their unique agro-climate characteristics. The top five positive and negative weather conditions that affect yield are shown in Figure 1. In Gampaha district (District_1) which is under wet zone, prescriptions occurring three months before inflorescence significantly enhance nut growth, while sunshine duration and temperature following inflorescence negatively impact on yield. This weather condition reflects the wet zone's moisture dependent physiology.

Kurunegala district (District_17) drives the same factors to Gampaha, both positive and negative influences prior and post inflorescence, describing intermediate zone significantly affect with precipitation, sunshine duration and mean temperature. However, Puttalam district (District_18) shows distinct weather patterns. The yield is enhanced by wind speed significantly alongside perception in before inflorescence, while post inflorescence sunshine duration, mean temperature, evapotranspiration adversely affects pollination success and nut retention in dry zone.

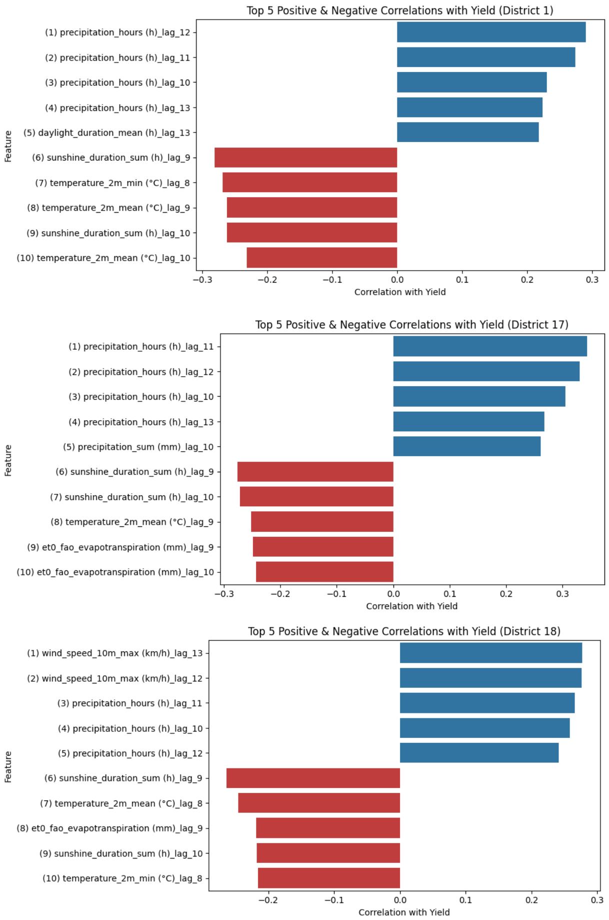

Figure 1: Top 5 Positive & Negative Correlations with Yield for Gampaha, Kurunegala & Puttalam

A correlation analysis is conducted for each district after determining the primary associated weather factors. Figure 2 illustrates the heatmap that delineates the linear relationships of the top five positive and negative factors with coconut yield, as well as the linear relationships among each factor. High positive correlations are represented in dark red, while high negative correlations are depicted in light blue. Identifying of the interrelationship between each factor in important to build the accurate predictive model without overlapping.

Future Outlook: Digital Twin Integration

The finding highlighted that specific lagged weather variables are the primary drivers of coconut yield fluctuation across Sri Lank's three

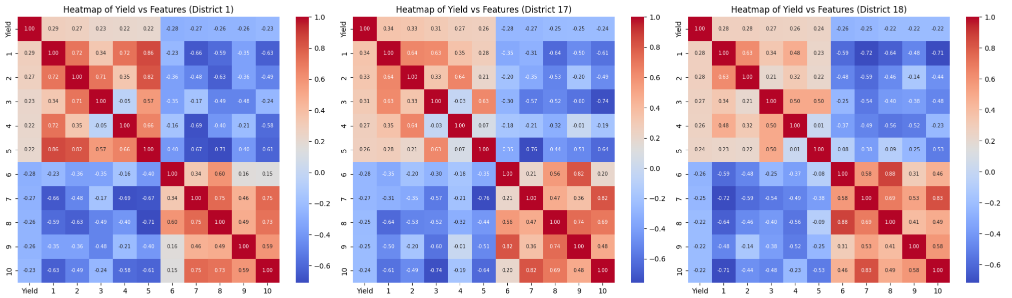

Figure 2: Heatmap of Yield vs Features for Gampaha, Kurunegala & Puttalam

coconut producing regions. However, to manage future risks, only historical analysis is not adequate. To translate these data insight into actionable strategies, the coconut supply chain requires real time monitoring facilitate with predictive analysis. This necessity makes the adoption of Digital Twin technology essential.

Digital twins denote the virtual duplication of real-world systems, providing a dynamic and data-driven representation of physical processes [5]. This emerging approach has gained significant attention across sectors such as healthcare, construction, and agriculture due to its ability to monitor operations, identify risks, and predict future outcomes using real-time data. The integration of artificial intelligence (AI), internet of things (IoT), sensors, and the blockchain with digital technology will be expected to redefine agricultural risk management.

By implementing digital twin technology integrate with weather relationships identified in this study, coconut production can build unprecedented resilience. Real time data from IoT sensors or weather API would enable continuous tracking of relevant weather variables. Accurate yield forecasts would be made possible by these data streams feeding into digital twin model trained on the district-specific connections found in this study. Through 'what-if' scenario modeling, stakeholders can anticipate outcomes and implement proactive strategies such as irrigation adjustments rather than reacting to crises after they occur.

Conclusion

This study demonstrates that coconut yield in Sri Lanka's three major producing districts is significantly influenced by specific and unique weather pattern across multiple temporal lags. For policymakers, these results emphasize the need to shift beyond general agricultural policies toward district-specific interventions that account for distinct agro-climatic risks, such as wind stress in Puttalam or rainfall variability in Gampaha. By shifting from reactive crisis management to proactive, data-driven decision-making with digital-twin, stakeholders can anticipate potential shortages more effectively and optimize resource allocation. This transition ultimately strengthens the resilience of the coconut supply chain, safeguarding the livelihoods of smallholder communities amid increasing climate uncertainty.

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Article by

Sachith Wathuyaya, Niles Perera

Department of Transport Management and Logistics Engineering, Faculty of Engineering