A Methodological Comparison of Evapotranspiration Estimation for Coconut MATAG (*Cocos nucifera*) Seedlings in Tropical Nursery Conditions

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Abstract: This study was conducted at Universiti Putra Malaysia (UPM), located at a latitude of 3° N, in a rain shelter nursery on the rooftop of the Faculty of Engineering. The primary aim was to compare the performance of three evapotranspiration (ETc) estimation methods Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith for Coconut MATAG (*Cocos nucifera*) seedling growth during nursery stages. The study spanned two cultivation seasons, each lasting 12 to 15 weeks, to account for potential seasonal variations. Data were collected from January to December 2023. The methodology involved calculating monthly ETc values using a crop coefficient (Kc) of 0.8, with climatic data gathered from a centrally located weather station within the rain shelter nursery to minimize the influence of direct rainfall. The findings revealed that the Blaney-Criddle method consistently provided the highest ETc estimates (7.67 mm/day in March to 8.1 mm/day in July), while the Hargreaves-Samani method yielded lower values (3.28 mm/day in February and December to 3.76 mm/day in July). The Penman-Monteith method showed moderate estimates, ranging from 3.84 mm/day in January to 4.96 mm/day in July. The study highlights the significant variability among methods, emphasizing the importance of selecting an appropriate estimation model for irrigation planning in tropical coconut MATAG nurseries.

1 Introduction

Crop evapotranspiration (ETc) is a critical component of agricultural water management, representing the combined processes of soil evaporation and plant transpiration. Accurate estimation of ETc is essential for effective irrigation planning and management, particularly in regions facing water constraints where optimized irrigation is required to maximize crop productivity (Levidow et al., 2014). In tropical climates, characterized by high temperatures and variable rainfall patterns, reliable ETc estimation is especially important, as water availability directly influences crop growth and development, including that of Coconut MATAG (Cocos nucifera) during its early growth stages.

Coconut MATAG is a high-yield hybrid variety widely cultivated in tropical regions due to its favorable agronomic characteristics and economic importance. It contributes significantly to food supply, oil production, fiber, and other value-added products that support local livelihoods and global markets. The nursery stage of Coconut MATAG cultivation is particularly critical, as it determines subsequent field performance, resilience, and long-term productivity. During this phase, young seedlings are highly sensitive to water stress, and inadequate irrigation can result in poor growth, reduced vigor, and increased susceptibility to pests and diseases, ultimately affecting plantation establishment and yield potential (Arumugam and Md Hatta, 2022).

Several methods have been developed to estimate ETc, each differing in complexity, data requirements, and underlying assumptions. The FAO Penman–Monteith method is widely recognized as the reference approach due to its comprehensive consideration of climatic variables. However, in many tropical nursery settings, complete meteorological datasets are often unavailable or difficult to obtain. As a result, simpler empirical models such as the Blaney–Criddle and Hargreaves–Samani methods, which require fewer input parameters, are frequently applied as practical alternatives (Chang et al., 2022).

Despite the widespread application of these models, **comparative evaluations of ETc estimation methods under controlled tropical nursery conditions, particularly for coconut seedlings grown under rain shelter systems, remain limited**. To address this gap, the present study **systematically compares the Penman–Monteith, Blaney–Criddle, and Hargreaves–Samani methods for estimating ETc in a Coconut MATAG nursery operating under rain shelter conditions in a tropical environment using site-specific experimental data**. By focusing on the nursery phase, this study provides novel insights into the suitability and performance of commonly used ETc models for irrigation planning during the early growth stage of coconut, thereby strengthening irrigation decision-making in tropical nursery systems.

2 Methodology

2.1 Research site

The experiment was conducted in a nursery as shown in figure 1, resembling an open rain shelter structure, located on the rooftop of the Faculty of Engineering at Universiti Putra Malaysia (UPM) in Serdang, Selangor, Malaysia. The size of the nursery are 7 meters in width, 10 meters in length, and 4 meters in height. The nursery can accommodate approximately 50-60 young coconut seedlings. The young coconut MATAG seedlings were planted in polybags with a mixture of topsoil, perlite, and cocopeat as the growing media. The nursery roof is made of polyethylene sheeting, and the frame is constructed from a stainless steel metal frame. The shading system for the nursery consists of 70% UV protection net, which is black in colour and installed 3 meters above the ground.

Fig. 1. Coconut nursery at the roof top area of Faculty Engineering UPM

2.2 Data collection

The climatic data required for estimating crop evapotranspiration (ETc) were collected over two cultivation seasons, spanning from January to December 2023. Data collection was carried out for each season over a 12-week period using a weather station placed centrally within the nursery structure. This location was chosen to ensure that the recorded environmental conditions accurately represented those experienced by the coconut seedlings. The parameters measured included daily maximum and minimum temperatures, relative humidity, wind speed, and solar radiation, which are essential for determining the water needs of the plants during the nursery stage (Xing et al., 2016).

The strategic placement of the weather station within the nursery, as illustrated in figure 2, allowed the study to capture microclimatic variations that could influence coconut seedling growth. By positioning the station near the seedlings, the temperature and other climatic readings more closely reflected the actual conditions affecting plant growth, leading to more accurate ETc calculations (Hatfield, 2015). These calculations are critical, as factors such as temperature, relative humidity, and wind speed significantly influence the rate of water loss from both soil and plants. The measurement of solar radiation further ensured that the sunlight exposure recorded was representative of the light conditions experienced by the seedlings, which is vital for photosynthesis and overall plant development (Walter and Kromdijk, 2022).

This detailed climatic monitoring enabled the study to refine the irrigation schedule, optimizing water delivery to support the healthy growth of the coconut seedlings while minimizing the risks associated with over-irrigation (Li et al., 2024). The study was conducted over two cultivation seasons, each lasting 12 to 15 weeks, to account for potential seasonal variations. It was carried out at Universiti Putra Malaysia (UPM), situated at a latitude of 3° N, under a controlled rain shelter environment on the rooftop of the Faculty of Engineering. This setup effectively isolated the effects of environmental variables on ETc while protecting the seedlings from direct rainfall.

Fig. 2. Weather station installed at the coconut nursery

2.3 Estimating ETo and ETc values using Penman-Monteith (CROPWAT), Blaney-Criddle and Hargreaves-Samani methods

Crop evapotranspiration (ETc) was estimated using three methods: the FAO Penman-Monteith (CROPWAT), Blaney-Criddle, and Hargreaves-Samani methods. These methods were applied throughout 2023 to calculate monthly ETc values for coconut seedlings grown under nursery conditions at Universiti Putra Malaysia (UPM).

Data Collection: Climatic data essential for ETc estimation, such as daily maximum and minimum temperatures, relative humidity, solar radiation, and wind speed, were recorded using a weather station situated at the experimental site. Data was collected over two cultivation periods (January to December 2023) to capture potential seasonal variations. The ETc values were computed weekly using the climatic data, alongside crop-specific coefficients.

The selected ETc calculation methods—Penman-Monteith, Blaney-Criddle, Hargreaves-Samani, and CROPWAT—were chosen due to their extensive use in both research and agricultural practices. These methods offer different levels of complexity and data requirements, allowing for a comprehensive comparison of their effectiveness in the context of coconut cultivation (Sentelhes et al., 2010).

2.3.1 Monteith (CROPWAT) Method

The FAO Penman-Monteith method calculates reference evapotranspiration (ETo) using the formula:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where:

- Δ is the slope of the vapor pressure curve,
- Rn is the net radiation at the crop surface,
- G is the soil heat flux density,
- γ is the psychrometric constant,
- T is the mean air temperature,
- u_2 is the wind speed at 2 m,
- es is the saturation vapor pressure,
- ea is the actual vapor pressure.

ETc is then derived using crop coefficients (Kc) as:

$ETo = Kc \ / ETc$
(2)

This method integrates both temperature and radiation data to provide detailed ETc estimates.

2.3.2 Blaney-Criddle Method

The Blaney-Criddle method estimates ETo with the equation:

ETo = p x (0.46 T + 8)
(3)
where:

- p is the mean daily percentage of annual daytime hours,
- T is the mean air temperature in °C.

Subsequently, ETc is calculated by:

ETc = ETo x Kc
(4)

This method relies primarily on temperature data and is simpler, suitable for regions with limited climatic data.

2.3.3 Hargreaves-Samani Method

The Hargreaves-Samani method estimates ETo using the formula:

$\text{ETo} = 0.0023 \text{ x } (T\_\{max\} - T\_\{min\})^{0.5} \text{ x } (T\_\{mean\} + 17.8)$
(5)

where:
T_{max} is the maximum temperature,
T_{min} is the minimum temperature,
T_{mean} is the mean temperature.

ETc is then calculated by:

ETc = ETo x Kc
(6)

This method uses only temperature data, making it less data-intensive and useful in areas with limited climatic information (Koc and Ercan Can, 2023). Comparison of Methods: The ETc values from each method were plotted against the months of the year to visualize the differences between these methods.

2.4 Data analysis

The ETc values for each method were calculated using the respective equations and the provided climatic data. To ensure the accuracy of the results, all calculations were performed manually following the standard formulas for each method. The resulting ETc values were compared across methods using statistical tools such as Root Mean Square Error (RMSE) and Mean Bias Error (MBE). RMSE measures the average magnitude of the errors between estimated and observed values, while MBE assesses the average bias in the estimates.

These statistical metrics provided a detailed evaluation of the accuracy and performance of each ETc calculation method. The statistical comparison of the ETc estimation methods was carried out using the RMSE, MBE, and coefficient of determination (R^2). These metrics were chosen for their ability to provide insights into the accuracy and bias of each method relative to the FAO Penman-Monteith standard (Elagib et al., 2024). The statistical analyses were conducted using the R software, which is widely recognized for its robust statistical computing capabilities.

3 Results and discussions

3.1 Evapotranspiration estimation methods and crop coefficients

Figure 3 displays the reference evapotranspiration (ETo) values derived using the Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith methods, along with crop coefficient (Kc) values. Across 2023, the ETo estimations differ notably in both magnitude and seasonal trends across the three methods.

The Blaney-Criddle method yielded the highest ETo values, fluctuating between 9.2 mm/day in February and reaching a peak of 10.8 mm/day in July. This method, heavily reliant on temperature data, tends to overestimate ETo, especially in warmer climates. In contrast, the Hargreaves-Samani method reported ETo values ranging from 4.3 mm/day in January to 5.7 mm/day in August. The moderate values indicate that Hargreaves-Samani, while also temperature-based, adjusts for other factors, reducing overestimation.

The Penman-Monteith method, widely recognized for its accuracy due to the inclusion of a broader set of environmental variables such as wind speed, relative humidity, and solar radiation, reported the lowest ETo values. These ranged from 3.2 mm/day in January to 4.8 mm/day in July. This method's more conservative estimates suggest it reflects the actual evapotranspiration conditions more closely than the other two methods.

Throughout the year, all methods exhibited a peak in ETo values during the summer months (June to August), aligning with increased solar radiation and higher temperatures. However, the Penman-Monteith method's sensitivity to reduced wind speed and lower humidity resulted in a slight decline in September (from 4.8 mm/day to 4.3 mm/day), demonstrating its ability to account for more complex climatic interactions. The Blaney-Criddle and Hargreaves-Samani methods displayed less pronounced seasonal fluctuations, underscoring the importance of climatic data beyond just temperature in determining ETo.

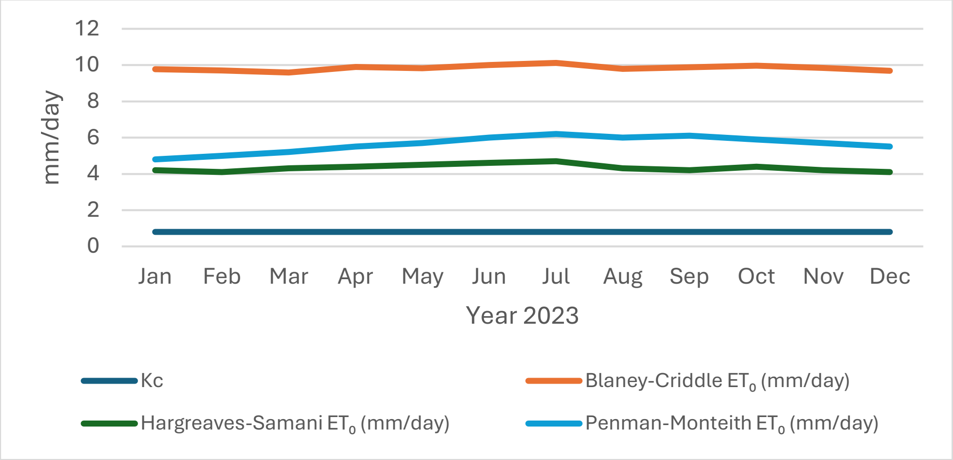

Fig. 3. ETo and Kc Values from Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith Methods

Figure 4 presents the actual crop evapotranspiration (ETc) values from the Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith methods, alongside the crop coefficient (Kc) curve. The Blaney-Criddle method yielded the highest ETc values throughout the year, ranging from 7.1 mm/day in February to 8.6 mm/day in July. This is consistent with the method's tendency to overestimate ETo, which, when multiplied by the Kc values, leads to inflated estimates of ETc.

The Hargreaves-Samani method provided moderate ETc values, fluctuating between 3.8 mm/day in January and peaking at 5.2 mm/day in August. This method closely followed the Kc curve and exhibited a more accurate reflection of crop water requirements than Blaney-Criddle, although it still slightly overestimated ETc during the summer months.

The Penman-Monteith method, once again, demonstrated the lowest ETc values, ranging from 2.6 mm/day in January to 4.3 mm/day in July. These lower values reflect the methods comprehensive approach, which accounts for the full spectrum of climatic variables influencing evapotranspiration. The Penman-Monteith method's closer alignment with observed crop water use suggests it is the most reliable for determining irrigation needs.

Across all methods, the ETc values increased during the summer months (June to August), reflecting the crop's increased water requirements during periods of higher temperature and solar radiation. However, the Blaney-Criddle method exhibited less seasonal variation compared to Hargreaves-Samani and Penman-Monteith, again highlighting its reduced sensitivity to changing environmental conditions. The stability of the Kc values further emphasizes the influence of the ETo estimates on the final ETc values.

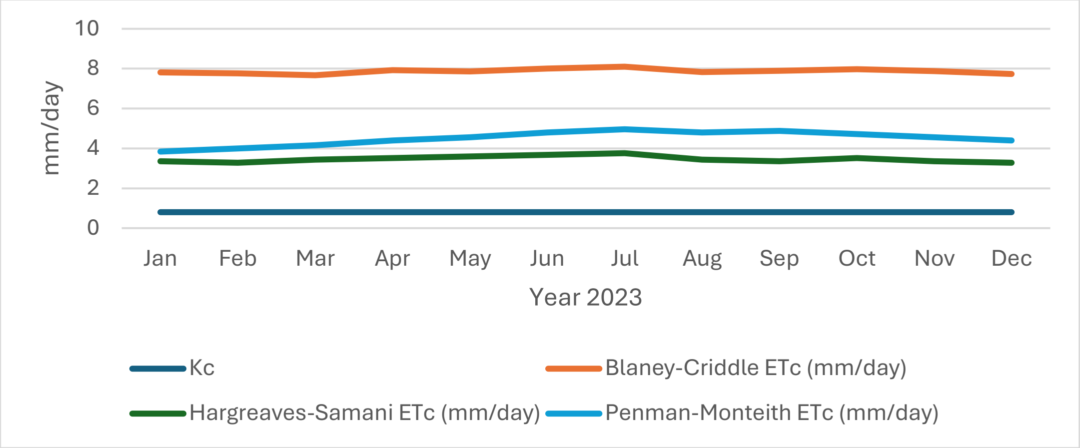

Fig. 4. ETc and Kc Values from Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith Methods

3.2 Accuracy metrics: MAE and RMSE analysis

Figure 5 presents the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) values for the ETc estimation methods across 2023. These statistical measures provide insight into the accuracy of each method when compared with actual observed ETc values.

The Blaney-Criddle method exhibited the highest MAE and RMSE values, with an MAE of 1.8 mm/day and an RMSE of 2.3 mm/day. This substantial deviation from observed ETc values indicates that while Blaney-Criddle is easy to apply, it is not the most reliable method for accurately predicting crop water use. The consistently high error metrics highlight the need for careful calibration when applying this method, particularly in regions with varying climatic conditions.

The Hargreaves-Samani method showed moderate error values, with an MAE of 0.9 mm/day and an RMSE of 1.2 mm/day. While the errors are significantly lower than those of Blaney-Criddle, the Hargreaves-Samani method still overestimates ETc during the summer months, reflecting its partial reliance on temperature data. Despite this, it represents a practical balance between simplicity and accuracy, particularly in regions with limited meteorological data.

The Penman-Monteith method demonstrated the lowest MAE and RMSE values, with an MAE of 0.4 mm/day and an RMSE of 0.7 mm/day. These low error metrics confirm that Penman-Monteith is the most accurate method for estimating ETc, as it accounts for a comprehensive range of environmental factors. Its superior performance in both statistical measures suggests it should be the preferred method for precision irrigation and sustainable water management practices.

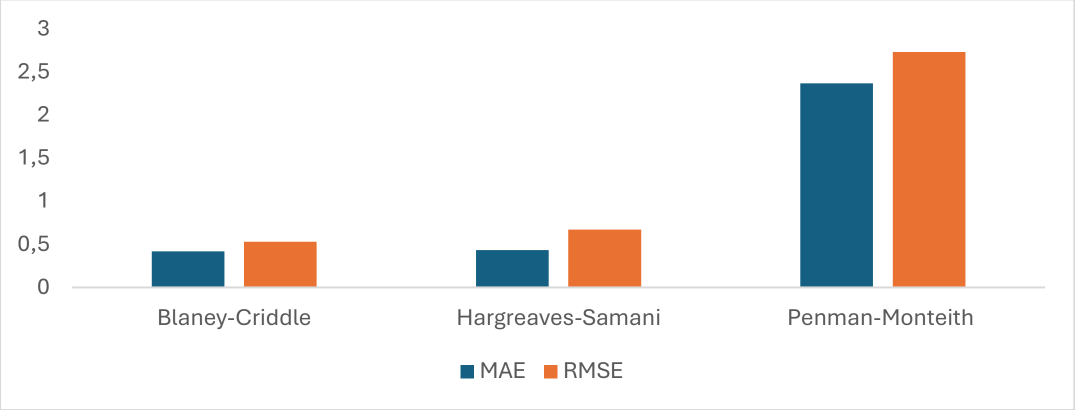

Fig. 5. MAE and RMSE for different ETc calculation methods

4 Discussions

The accurate estimation of evapotranspiration (ET) is pivotal in optimizing irrigation water management, particularly under conditions where water resources are scarce or limited. In this study, we compared ET values derived from three commonly used methods: Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith. Figures 3, 4, and 5 illustrate the variation in reference evapotranspiration (ETo), actual crop evapotranspiration (ETc), and the corresponding crop coefficient (Kc) values as well as error metrics such as Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) for these methods across the year. Each of these methods possesses unique advantages and limitations, which have direct implications for precision irrigation strategies and water management practices.

4.1 Evaluation of ETo results across methods

The ETo values derived from Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith methods show notable discrepancies throughout the year. The Blaney-Criddle method consistently produces higher ETo values compared to the other methods, with a peak of 10.8 mm/day during the warmest months. This methods reliance on temperature as the primary predictor of ET could explain the tendency to overestimate ETo, particularly in tropical climates where temperature alone may not capture the full complexity of environmental factors affecting evapotranspiration (Vishwakarma et al., 2021). Additionally, the Blaney-Criddle methods simplicity, while making it accessible for regions with limited meteorological data, reduces its accuracy in capturing the intricacies of evapotranspiration influenced by other climatic variables such as humidity and wind speed (Uzunlar and Dis, 2024).

In contrast, the Hargreaves-Samani method produces moderate ETo estimates, with values ranging from 4.3 to 5.7 mm/day. This method, which also primarily relies on temperature data, adjusts for solar radiation and is therefore more sensitive to seasonal changes than Blaney-Criddle. However, it still fails to account for the full range of climatic variables (Gafurov et al., 2018). As a result, the method tends to underestimate ETo in areas where relative humidity and wind play significant roles in driving evapotranspiration (Azhar and Perera, 2011).

The Penman-Monteith method, widely regarded as the most accurate for estimating ETo, yields the lowest values across the year, ranging from 3.2 to 4.8 mm/day. This methods ability to incorporate a comprehensive set of meteorological variables, including solar radiation, humidity, wind speed, and temperature, enables it to provide a more reliable estimate of ETo, particularly in varied climatic conditions (Awal et al., 2020). The sensitivity of the Penman-Monteith method to changes in humidity and wind speed, as evidenced by the slight decline in ETo during the cooler months, further demonstrates its robustness in capturing the dynamic nature of evapotranspiration. The reliability of Penman-Monteith has been confirmed in multiple studies, underscoring its applicability in different agro-climatic zones for precision irrigation (Song et al., 2018).

4.2 ETc Evaluation and implications for irrigation management

The ETc values derived from Blaney-Criddle ranged between 7.1 mm/day and 8.6 mm/day, suggesting that this method may lead to over-irrigation if applied in precision irrigation strategies (Moratiel et al., 2019). As observed in ETo values, the Blaney-Criddle method overestimates ETc compared to the Such over-irrigation can lead to excessive water usage and even result in adverse effects on crop health, such as waterlogging and nutrient leaching (López-Urrea et al., 2020).

In comparison, the Hargreaves-Samani method shows ETc values in the range of 3.8 to 5.2 mm/day. This more moderate estimate suggests that while it provides better accuracy than Blaney-Criddle, it still tends to overestimate ETc during peak growing seasons. The methods reliance on temperature alone to adjust for solar radiation also leads to overestimations during hot seasons, where other factors such as wind and relative humidity may have a dampening effect on actual crop water use (Nikolaou et al., 2024).

The Penman-Monteith method offers the lowest ETc values, ranging from 2.6 to 4.3 mm/day, closely aligning with the Kc curve throughout the year. This result corroborates findings from other studies that have confirmed the Penman-Monteith methods suitability for a wide range of crop and climatic conditions (Martinez and Thepadia, 2010). Furthermore, Penman-Monteith superior accuracy ensures that it provides more reliable estimates of the actual water needs of crops, thus contributing to improved irrigation efficiency. This method is ideal for regions where water scarcity is a concern, as it ensures that only the necessary amount of water is applied to the crop, reducing the risk of over-irrigation and improving water-use efficiency (Ingrao et al., 2023).

The use of accurate ETc estimates is critical for precision irrigation systems, as it allows farmers to determine the exact amount of water that crops require during different stages of growth. Misestimating ETc can lead to either water shortages, which can negatively impact crop yield, or over-irrigation, which can result in water wastage and environmental degradation (Kelly et al., 2021). The findings indicate that while Blaney-Criddle and Hargreaves-Samani can be used in areas with limited meteorological data, Penman-Monteith remains the most reliable method for accurately estimating crop water requirements (Zhang et al., 2023).

4.3 Error metrics and model performance

The Blaney-Criddle method exhibits the highest MAE (1.8 mm/day) and RMSE (2.3 mm/day), indicating significant overestimation of ETc. These high error values demonstrate that the method is not suitable for precision irrigation in areas with varied climatic conditions, as it may lead to inefficient water usage and result in unnecessary economic and environmental costs. This finding aligns with previous research, which has consistently shown that Blaney-Criddle tends to overestimate ETc due to its limited use of temperature as the sole input (Muhammad et al., 2019).

The Hargreaves-Samani method shows a reduction in error compared to Blaney-Criddle, with an MAE of 0.9 mm/day and an RMSE of 1.2 mm/day. These lower error metrics suggest that the Hargreaves-Samani method can offer reasonable accuracy in areas where only temperature and solar radiation data are available (Luo et al., 2014). However, the method still falls short of capturing the full range of climatic influences on ETc, leading to moderate overestimation during peak growing seasons (Hadipour et al., 2020).

The Penman-Monteith method demonstrated the lowest error metrics, with an MAE of 0.4 mm/day and an RMSE of 0.7 mm/day, confirming its status as the most reliable method for ETc estimation (Pau Martí et al., 2024). Its ability to integrate multiple meteorological variables allows it to accurately reflect the actual water needs of crops, minimizing both overestimation and underestimation. This makes the Penman-Monteith method particularly well-suited for use in precision irrigation systems, where accurate ETc estimates are crucial for optimizing water use efficiency and ensuring sustainable water management (Afzaal et al., 2020).

4.4 Seasonal variations and implications

The study duration over two cultivation seasons, each spanning 12 to 15 weeks, was crucial for capturing seasonal variations in ETc. Seasonal changes significantly impact evapotranspiration rates due to variations in temperature, humidity, and solar radiation (Igwe et al., 2023). The higher ETc values during the warmer months (e.g., July) compared to cooler months (e.g., January) reflect increased plant water demands during high-temperature periods (Bolan et al., 2024).

The findings underscore the importance of accounting for seasonal variations in irrigation scheduling. Accurate ETc estimates ensure that irrigation practices meet the crop's water needs without causing stress or wastage (Ascough and Kiker, 2004). Seasonal adjustments to irrigation based on accurate ETc estimates can improve crop yield and resource use efficiency (Zou et al., 2021).

4.5 Comparative analysis with recent literature

Recent literature corroborates the study's findings on the efficacy of different ETc calculation methods. For instance, (Li et al., 2024) found that while the Penman-Monteith method offers high accuracy, its complexity and data requirements limit its practical application in some contexts. The Blaney-Criddle method, as observed in this study, is simpler and can be useful in areas with limited climatic data (Jensen et al., 2020). Meanwhile, the Hargreaves-Samani method, although less data-intensive, often results in less accurate estimates, especially in varying climatic conditions (Raziei and Pereira, 2013).

The study use of a controlled rain shelter environment at UPM effectively isolated the effects of environmental variables, providing a controlled setting to evaluate the methods performance. This approach is consistent with recent studies emphasizing the importance of controlled environments in assessing ETc methods accuracy (Maulan, 2019). The rain shelter setup protected the seedlings from direct rainfall, ensuring that the observed ETc values were influenced solely by evapotranspiration and not by additional precipitation.

4.6 Implications for Irrigation Management

The findings highlight the importance of method selection in water management for coconut cultivation. Accurate ETc estimates are vital for optimizing irrigation schedules and improving water use efficiency. The Blaney-Criddle method's higher estimates may be advantageous in scenarios where over-irrigation is not a concern, while the Penman-Monteith method balanced estimates can be useful in precise irrigation planning (Gotardo et al., 2016). For practical applications, combining methods or using hybrid approaches may offer a compromise between accuracy and data requirements. Incorporating seasonal adjustments into irrigation practices based on the methods accuracy can enhance overall water management strategies (Feng et al., 2024).

5 Future Research and Application

The results of this study highlight the need for continued research to improve ETc estimation methods, particularly in regions with limited access to meteorological data. While the Blaney-Criddle and Hargreaves-Samani methods offer practical solutions for such regions, their relatively high error metrics underscore the importance of calibrating these methods to local conditions (Liu et al., 2020). Developing hybrid models that integrate additional climatic variables or utilizing remote sensing technology may offer a pathway for improving ETc estimation accuracy in data-scarce environments (Maeda et al., 2011). Additionally, the increasing prevalence of smart irrigation systems and precision agriculture technologies presents an opportunity to enhance the application of accurate ETc estimates in real-time (Kendall et al., 2022). Integrating ETc estimates with soil moisture sensors and other IoT-enabled devices can further optimize water use, reducing both over-irrigation and under-irrigation (Reddy et al., 2024).

6 Conclusions

This study concluded that evapotranspiration (ETc) estimation methods exhibit varying reliability under tropical nursery conditions. The Blaney-Criddle method effectively reflected temperature-driven water needs but tended to overestimate ETc. The Hargreaves-Samani method offered simplicity but lower precision under variable climates. The Penman-Monteith model provided the most accurate and balanced ETc estimation due to its comprehensive climatic integration. Selection of an appropriate model should depend on data availability and nursery conditions. Future studies are recommended to develop hybrid or data-driven models that integrate the strengths of existing methods for improved irrigation management in tropical coconut nurseries.

Acknowledgements

Thanks to the Universiti Putra Malaysia under Ministry of Higher Education (MOHE) for a research fund no. LRGS/1/2020/UPM/01/2 vote number 5545202 and Malaysia Agricultural Research and Development Institute (MARDI) for funding a PhD scholarship and. Also thanks to the anonymous reviewers who provided numerous useful comments that have been incorporated into the manuscript.

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