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Crop Coefficients of Paddy and Evapotranspiration in the Minapadi Model System Applying Nonpowered Automatic Fertigation

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Abstract: In irrigation and agricultural planning, the crop coefficient value plays an important role in calculating water planning on land. This study aims to calculate the crop coefficient (Kc) of rice in a Nonpowered Automatic Fertigation (FONi) irrigation system combined with a minapadi system as a reference for irrigation planning. This study was conducted experimentally for 99 days in Dramaga, Bogor, using the FONi Minapadi system consisting of a fiberglass tank, a water supply tank, and an automatic float to maintain the water level. Actual evapotranspiration (ETa) data were calculated based on water balance, while potential evapotranspiration (ETo) was modeled using five methods: Penman-Monteith, Turc, Hargreaves, Makkink, and Blaney-Criddle. Model validation was performed using linear regression against the Penman-Monteith method as the standard reference. The results show that the total ETa during the observation period was 421.93 mm. Among the ETo calculation methods, the Turc model provided results closest to the Penman-Monteith method, with a coefficient of determination (R^2) of 0.741 and the lowest sum of squares error (SSE) of 56.026. The calculated Kc values varied throughout the rice growth phase, with the highest value of 1.84 observed during the reproductive phase. The relatively high Kc value reflects significant water demand in the FONi Minapadi system, influenced by system characteristics and environmental conditions. This study concludes that the FONi Minapadi system has the potential to improve irrigation management efficiency in integrated agriculture. However, further research is needed to understand the influence of technical and environmental factors on the Kc value and to compare it with other irrigation systems.

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1. Introduction

In irrigation planning, water requirements are calculated using the crop evapotranspiration approach. Evapotranspiration is the evaporation of water from plant leaves or crowns, either as a result of metabolism or other activities. Evapotranspiration can also be defined as the total amount of water returned to the atmosphere from the soil surface, water bodies, and vegetation due to the influence of climatic and physiological factors of vegetation [1]. From a linguistic perspective, evapotranspiration is a combination of two terms: evaporation, which refers to the evaporation of water from surfaces unrelated to metabolic activity, and transpiration, which is the opposite and is closely related to plant metabolic activity. In real-world conditions, distinguishing between evaporation and transpiration is very difficult, especially when the soil is covered by vegetation. The magnitude of evapotranspiration can be directly measured using instruments such as an evapotranspirometer or lysimeter. However, both tools are quite rare and also considered quite expensive [2]. Several approaches can be taken, such as using an evapotranspiration model where actual evapotranspiration (ETa) is obtained from a function involving the plant coefficient (Kc) and reference or potential evapotranspiration (ETo). Many potential evapotranspiration models can be used. A study attempted to evaluate methods for estimating potential evapotranspiration rates by comparing several methods, including the Blaney-Criddle method, the Linacre-Hoobs method, the Kharrufa method, the Romaneko method, the Hargreaves method, the Makkink method, the Turc method, the Jensen-Haise method, and the Penman method. All the methods mentioned were compared with the standard method recommended by the Food and Agriculture Organization (FAO), namely the Penman-Monteith method. FAO recommended the Penman-Monteith method as the standard reference because it is considered the best method. This is because the Penman-Monteith method has an error value of 0.32 compared to other methods, which range from 0.56 to 1.29 [2], [3].

The *Kc* value is divided into three growth phases, namely *Kc* at initiation, *Kc* in mid-season, and *Kc* at the end of the season. Take the example of cereal crops, particularly rice. The *Kc* values for rice are 1.05, 1.02, and 0.90–0.60, respectively. The *Kc* values listed are *FAO* recommendations, which are not always applicable. The calculation of *Kc* values depends on the calculation approach, assumptions used, irrigation and planting methods, and many other factors. For instance, in the *SRI* irrigation system, the growth phase is divided into five stages: the initial phase, the vegetative phase, the flowering phase, the grain filling phase, and the maturation phase, with *Kc* values of 0.32; 0.71; 1.58; 1.5; and 0.59, respectively [4].

IPB University is currently developing a new irrigation system called the Nonpowered Automatic Fertigation (In Bahasa Indonesia is Fertigator Otomatis Nirdaya - FONi). FONi originated from the application of the evapotranspirative irrigation concept, which is used to meet plant water needs without using electricity. It consists of a series of pots connected by pipes and linked to a water supply tank that also functions as a water level regulator, forming a connected vessel system [5]. FONi technology has been demonstrated and tested in community service activities conducted in the city of Tasikmalaya, specifically at Madrasah Al-Manshur and the Siliwangi University campus, proving its ability to produce sustainable organic vegetables, particularly in meeting consumer needs [6]. There is another interesting agricultural concept known as integrated agriculture and fisheries, or more commonly referred to as minapadi. The minapadi system involves raising fish among rice plants as an interplanting method between two rice-growing seasons or raising fish as an alternative to cash crops in rice fields [7].

From the above statement, it can be concluded that the combination of FONi and Minapadi has good potential for the future. However, technical issues such as the *Kc* value of rice plants in the combined system must be identified. This study attempts to calculate the *Kc* value of rice plants in the combined system between FONi and Minapadi as a reference for planning similar irrigation systems in the future.

2. Methods

2.1. Time, Location, and Research Design

The research was conducted experimentally from May 27, 2024, to September 2, 2024 (99 days). The planting test was carried out on the FONi Minapadi system assembled on Carang Pulang, Dramaga, Bogor Regency, precisely at coordinates 6°32'55.7“S, 106°43'56.2”E. The FONi Minapadi system was designed by connecting several interconnected fiberglass tanks using 1/2" pipes and connected to a water level control bucket. The system layout can be seen in Figure 1.

Figure 1 shows the layout of the FONi Minapadi system used. Rice fields are replaced with fiberglass tanks, particularly in Control Box 1, Control Box 2, and Rice Control Box. Fish farming is carried out in three tanks, namely Control Box 1, Control Box 2, and Fish Control Box. A mobile weather station is installed at a height of 2 meters above ground level to measure weather and climate parameters. A drain is used to remove excess water caused by rain. The control bucket is used to maintain water level. The water level is maintained at 17.5 cm above ground level using a growing medium consisting of a mixture of native soil and commercial growing medium.

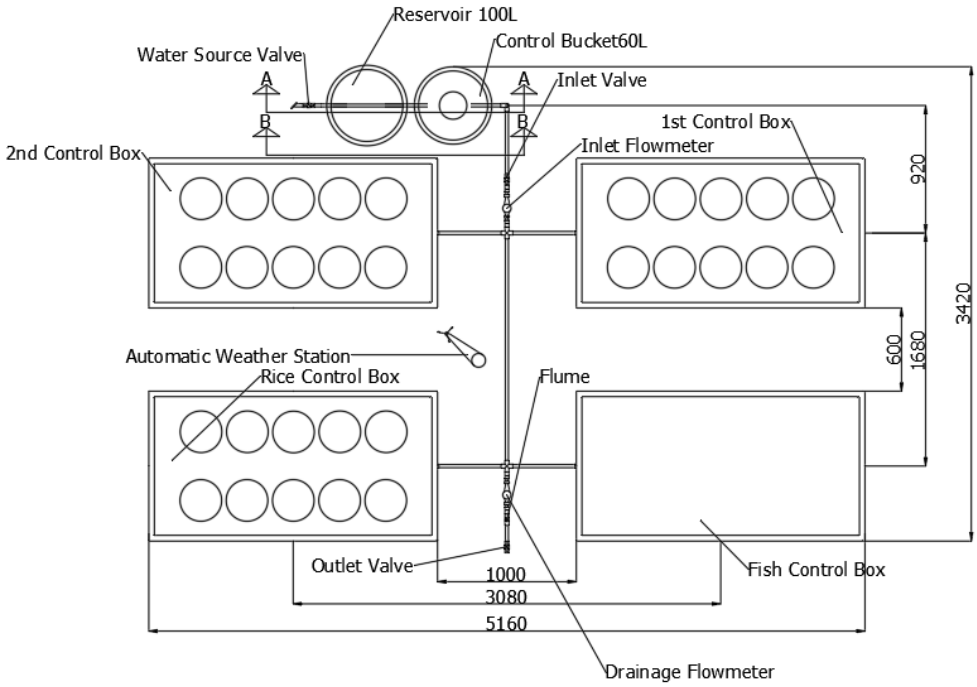

Figure 1. Plan of FONi system for minapadi model (Unit of length in mm) [8]

2.2. Evapotranspiration Analysis and Crop Coefficients

The initial analysis was conducted using the water balance as presented in Equation 1.

$$Ir + R = D + ETa + \Delta TMA \quad (1)$$

Where *Ir* is irrigation water (mm), *R* is rainfall (mm), *D* is drainage (mm), *ETa* is actual evapotranspiration (mm), and *ΔTMA* is change in water level (mm). The water level is maintained by a control box at a certain height, so it can be assumed that there is no change in water level in the box. The analysis was conducted using a comprehensive, system-wide approach rather than a subsystem-by-subsystem approach. By eliminating changes in water level, the value of *ETa* can be expressed as follows:

$$ETa = Ir + R - D \quad (2)$$

Crop evapotranspiration can be expressed as follows [9]:

$$ETc = Kc \times ETo \quad (3)$$

Where *ETc* is crop evapotranspiration (mm). Crop evapotranspiration can be approximated by actual evapotranspiration, which makes the equation for obtaining the *Kc* value as follows:

$$Kc = \frac{ETa}{ETo} \quad (4)$$

ETo modeling is performed using several approaches. One study states that several *ETo* calculation methods are quite good, namely Hargraves, Makkink, Turc, and Blaney-Crriddle, where the Penman-Monteith method is considered the control for all the methods mentioned above [10]. All the methods mentioned will be statistically tested against the Penman-Monteith method. The Penman-Monteith model was chosen as a reference because this method is recommended by the FAO and has a clear reference in Indonesia as stipulated in SNI 7745-2012. All *ETo* calculation methods can be stated as follows [11], [12], [13], [14], [15], [16]:

$$ET_{0-PM} = \frac{0{,}408\Delta R_n + \gamma \frac{900}{(T+273)} U(e_s - e_a)}{\Delta + \gamma(1 + 0{,}34U)} \quad (5)$$

$$ET_{0-H} = 0{,}000939\sqrt{T_x - T_n}(T_a + 18{,}8)Ra \quad (6)$$

$$ET_{0-M} = 0{,}61 \frac{\Delta}{\Delta + \gamma} \frac{Rs}{\lambda} \quad (7)$$

$$ET_{0-T} = 0{,}013 \frac{T_a}{T_a + 15}(Rs + 50)\left(1 + \frac{50 - RH}{70}\right) \quad (8)$$

$$ET_{0-BC} = p(0{,}457T_a + 8{,}128) \quad (9)$$

Where ET_{0-PM} is the Penman-Monteith model potential evapotranspiration (mm), ET_{0-H} is the Hargreaves model potential evapotranspiration (mm), ET_{0-M} is the Makkink model potential evapotranspiration (mm), ET_{0-T} is the Turc model potential evapotranspiration (mm), ET_{0-BC} is the Blaney-Criddle model potential evapotranspiration (mm), Δ is the slope of the vapor pressure curve against temperature (kPa/°C), R_n is net solar radiation above the plant surface (MJ/m²/day), γ is the psychrometric constant (kPa/°C), *U* is wind speed at 2 m above the ground surface (m/s), e_s is saturated vapor pressure (kPa), e_a is actual vapor pressure (kPa), T_x is the maximum temperature (°C), T_n is the minimum temperature (°C), T_a is the average temperature (°C), *Ra* is solar radiation above the atmosphere (MJ/m²/day), *Rs* is solar radiation (MJ/m²/day), λ is the latent heat of evaporation (MJ/kg), *RH* is air humidity (%), *p* is the percentage of average monthly daylight hours relative to the total daylight hours in a year.

3. Result and Discussion

Water balance calculations and analysis were performed by measuring irrigation water, rainfall, and drainage. Changes in water level were considered negligible because the water level was regulated and controlled by an automatic float in the control bucket. This analysis used Equation 2 to obtain actual evapotranspiration. Irrigation water and rainfall are considered as water variables entering the system, while drainage and actual evapotranspiration are considered as water variables exiting the system. Irrigation and drainage are obtained from meter readings divided by the total area of the tank used so that irrigation and drainage have the same unit of length, which also applies to rainfall and evapotranspiration. Calculations are performed daily and accumulated over the observation period, with the accumulated values of water entering and exiting the system shown in Figure 2.

Figure 2 shows the accumulation of irrigation, rainfall, drainage, and actual evapotranspiration. The total water inflow into the system is 737.92 mm, and the total water outflow from the system is also 737.92 mm, consisting of 456.00 mm of rainfall; 281.92 mm of irrigation water; 315.99 mm of drainage water; and 421.93 mm of actual evapotranspiration. The four *ETo* calculation methods as stated in Equations 6, 7, 8, and 9 were tested for validity against the Penman-Monteith method through linear regression. Model validation can be seen in Figure 3.

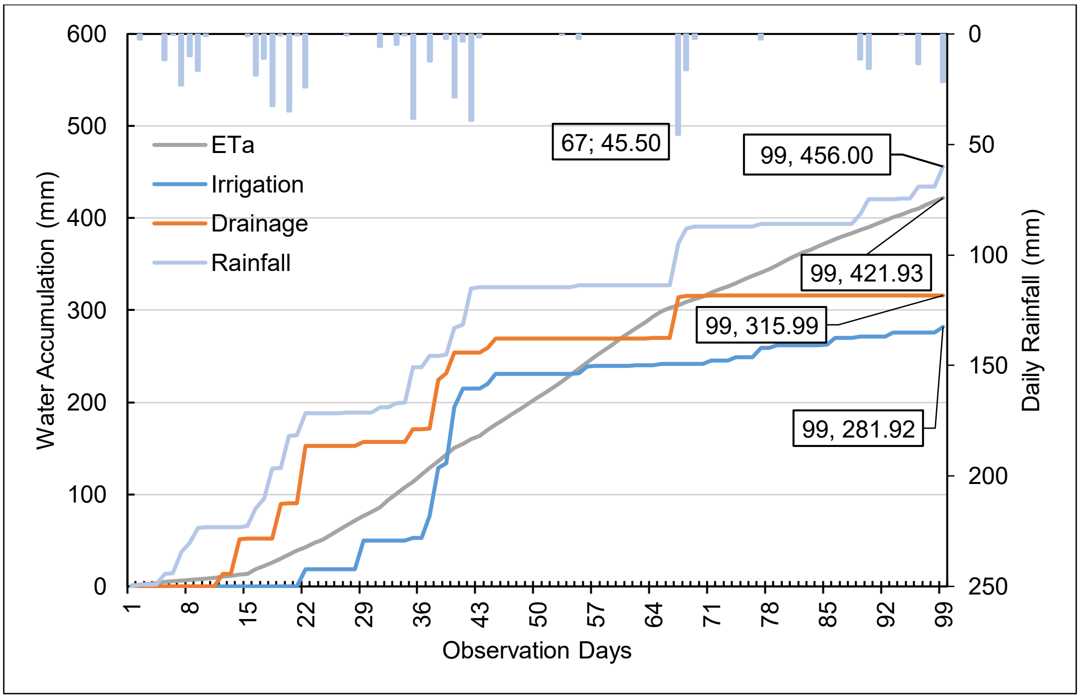

Figure 2. Accumulation of Water Components in the System

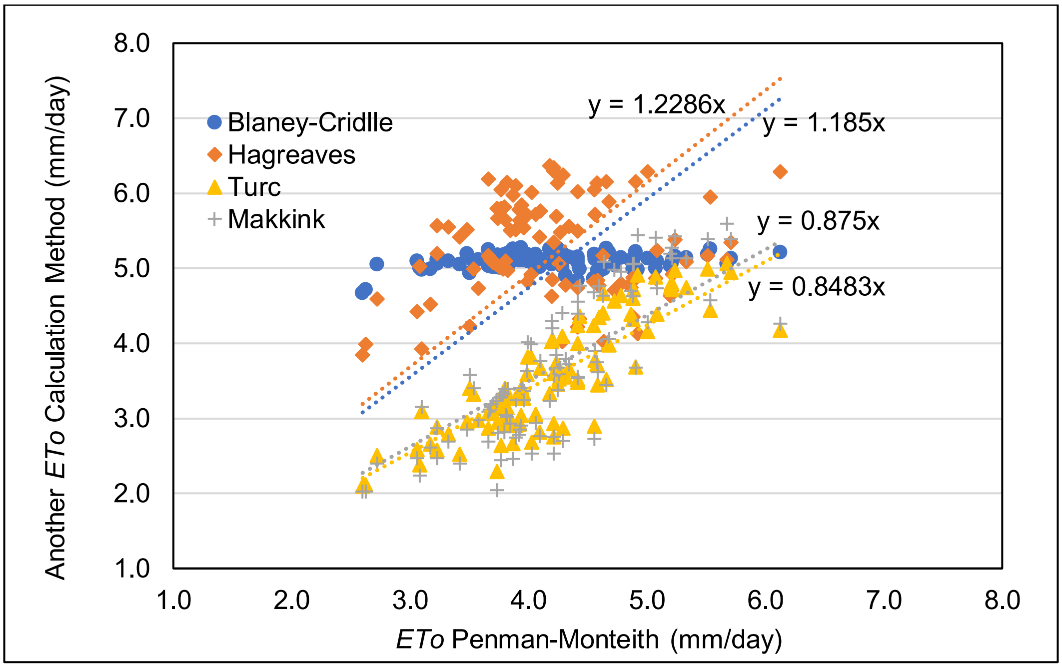

Figure 3. *ETo* Models Validation

The validation of the potential evapotranspiration model compared to the Penman-Monteith method presented in Figure 4 is quite diverse. The validation was conducted without an intercept to assume that each linear regression line passes through the point (0,0). An analysis of the coefficient of determination *(R^2)* and an error test in the form of the sum of squared errors *(SSE)* was performed on the model, considering the intercept in the linear regression model. The R^2 values for each model—Blaney-Criddle, Hargreaves, Makkink, and Turc—relative to the Penman-Monteith model are 0.071, 0.017, 0.691, and 0.741, respectively; while the *SSE* values are 124.518; 191.469; 59.034, and 56.026, respectively. Based on this analysis, the Turc model is considered the best model that closely approximates the Penman-Monteith model compared to the other models. This can be seen from the relatively good R^2 value of 0.741 and the lowest *SSE* value of 56.026. The calculation of the *Kc* value based on Equation 4 of the Turc and Penman-Monteith models. The comparison of accumulated *ETa* with *ETo* can be seen in Figure 4.

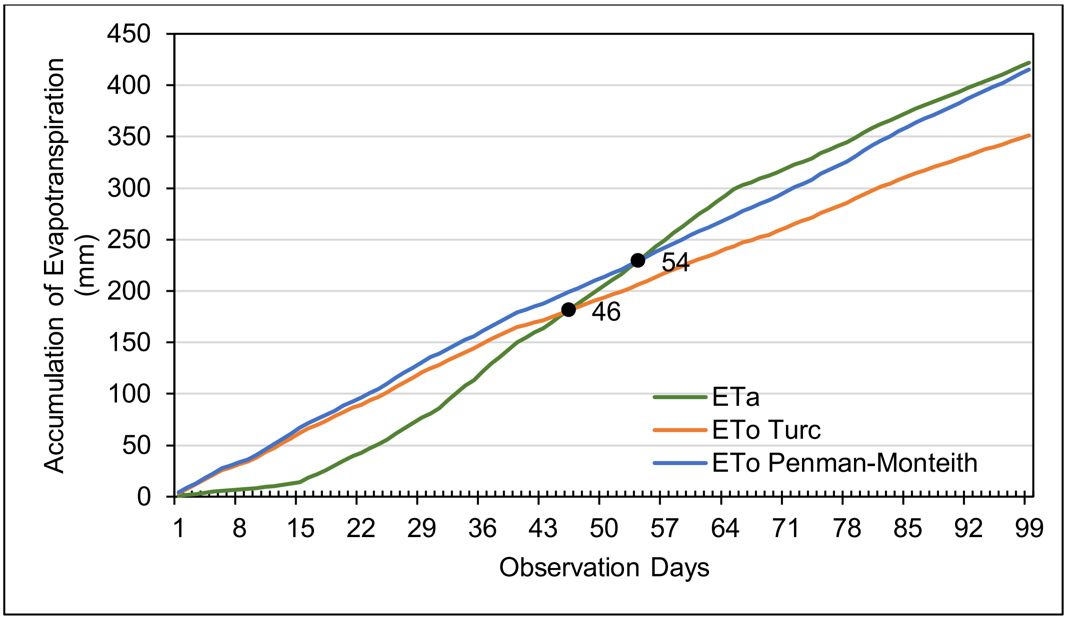

Figure 4. Comparation of Evapotranspiration

Figure 4 shows the accumulation of evapotranspiration during 99 days of observation, comparing *ETa* and *ETo* calculated using the Turc and Penman-Monteith methods. The analysis results show that *ETa* values are consistently higher than *ETo*, especially after days 46 and 54, indicating that the actual rate of water loss exceeds the potential estimate. The Penman-Monteith method produces estimates that are closer to *ETa* than the Turc method, so it can be concluded that the Penman-Monteith method is more accurate in estimating potential evapotranspiration under these conditions. The accumulation trends of the three curves are almost linear, although there are differences in the accumulation rates at the beginning and end of the observation period.

The calculation of *Kc* values is divided into four planting phases, namely early growth, vegetative growth, fertilization, and seed maturation. The early growth phase is calculated from the first day of observation to the 15th day of observation, the vegetative phase from the 16th day of observation to the 30th day of observation, the flowering phase from the 31st day of observation to the 65th day of observation, and the seed maturation phase from the 66th day of observation to the 99th day of observation. Graphically, the *Kc* values for each growth phase can be seen in Figure 5.

The crop coefficient values presented in Figure 6 show that in the FONi Minapadi system, both the Penman-Monteith and Turc models tend to have higher values in the last three phases compared to the study conducted by Khalid et al. (2019), in which rice was planted in swampy fields. This indicates that in the FONi Minapadi system, plants tend to require more water for metabolic activities, with the highest water demand occurring during the flowering phase using the Turc *ETo* method, with a *Kc* value of 1.84.

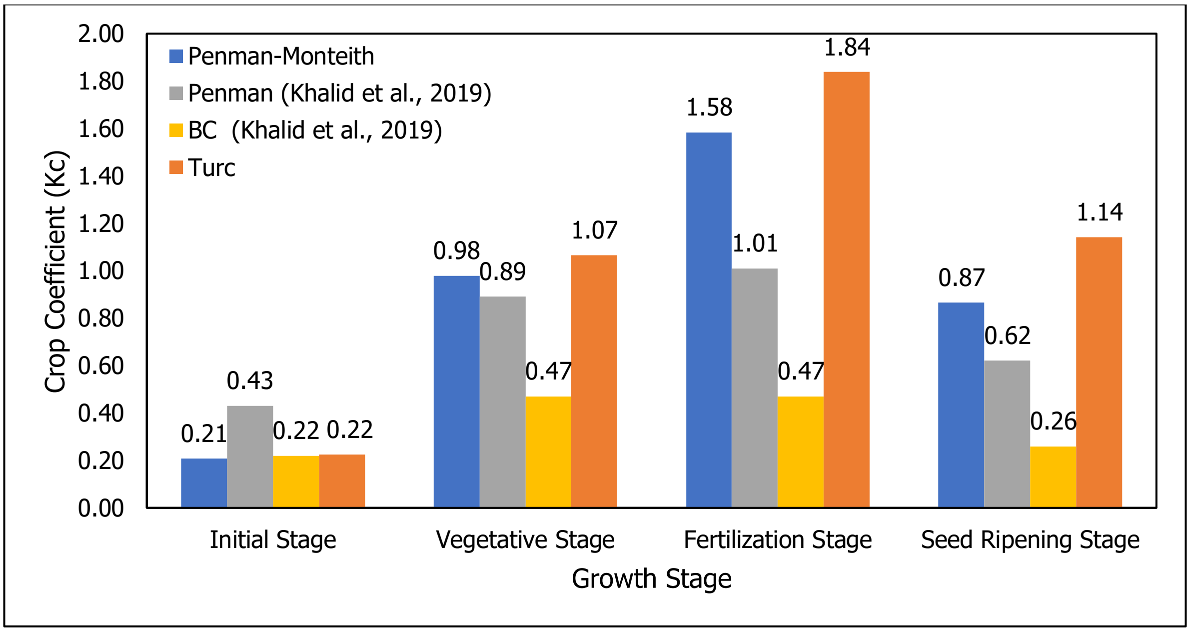

Figure 5. Value of Crop Coefficient [17]

4. Conclusion

This study shows that the FONi Minapadi system is capable of supporting irrigation management with a total actual evapotranspiration *(ETa)* value of 421.93 mm during the observation period. The Turc model was found to be comparable to the Penman-Monteith method in estimating potential evapotranspiration *(ETo),* with a coefficient of determination *(R^2)* of 0.741 and a sum of squared errors *(SSE)* of 56.026. The plant coefficient *(Kc)* values obtained showed variations across growth phases, with the highest value of 1.84 during the flowering phase. This relatively high *Kc* value indicates significant water requirements in the system; however, further study is needed to understand the influencing factors and compare it with other irrigation systems. These findings suggest that the FONi Minapadi system has the potential to support irrigation efficiency in integrated agriculture.

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