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Water demand of black pepper (*Piper nigrum* L.) determined by NDVI*

Demanda hídrica de pimienta negra (*Piper nigrum* L.) determinada por NDVI

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Abstract

Introduction. Water scarcity compromises agricultural productivity and requires precise management tools. Normalized Difference Vegetation Index (NDVI) emerges as an effective alternative for estimating crop coefficient and monitoring crop water needs. **Objective.** To estimate the water demand of black pepper (*Piper nigrum* L.) during the flowering phase in the Northeast region of Pará, by means of satellite images to obtain the NDVI and, from it, the estimation of the crop coefficient. **Materials and methods.** The study was conducted from 2016 to 2018 in the Avelinos community, Santa Luzia do Pará, Brazil, in an area cultivated with black pepper that was 1, 2, and 3 years old. Coordinates were obtained by GPS and Landsat 8 images were used to calculate NDVI. The crop coefficient (Kc) was estimated using the SAFER algorithm based on NDVI, and the crop evapotranspiration (ETc) was calculated by multiplying Kc by the reference evapotranspiration. **Results.** In areas with 1 and 2 years of cultivation, Kc ranged from 0.22 to 1.00, while in the area with 3 years of cultivation, values ranged from 0.11 to 0.33, which indicates low vegetative vigor and water stress. The estimated water demand for the flowering phase was 2.50, 2.62, and 1.30 L m^2 day^{-1} for areas with 1, 2, and 3 years of cultivation, respectively. **Conclusions.** NDVI-based estimates effectively captured crop water requirements and vegetative vigor across different cultivation ages, revealing that the oldest area exhibits lower water demand coupled with elevated water stress. Given the absence of stage-specific values for black pepper, these estimated parameters provide a fundamental basis for refining irrigation management in Northeastern Pará.

Keywords: Remote sensing, crop coefficient, precision agriculture, irrigation.

Resumen

Introducción. La escasez de agua compromete la productividad agrícola y requiere herramientas de gestión precisas. El índice de vegetación de diferencia normalizada (NDVI) surge como una alternativa eficaz para estimar el coeficiente de cultivo y monitorear los requerimientos hídricos de los cultivos. **Objetivo.** Estimar la demanda hídrica del cultivo de pimienta negra (*Piper nigrum* L.) durante la fase de floración en la región noreste de Pará, utilizando imágenes satelitales para obtener el NDVI y, a partir de él, estimar el coeficiente de cultivo. **Materiales y métodos.** El estudio se realizó de 2016 a 2018 en la comunidad Avelinos, Santa Luzia do Pará, Brasil, en un área cultivada con pimienta negra de 1, 2 y 3 años. Se obtuvieron coordenadas por GPS y se utilizaron imágenes de Landsat 8 para calcular el NDVI. El coeficiente de cultivo (Kc) se estimó utilizando el algoritmo SAFER a partir del NDVI, y la evapotranspiración del cultivo (ETc) se calculó multiplicando Kc por la evapotranspiración de referencia. **Resultados.** En áreas con 1 y 2 años de cultivo, el Kc osciló entre 0,22 y 1,00, mientras que, en el área con 3 años de cultivo, los valores estuvieron entre 0,11 y 0,33, lo que indica bajo vigor vegetativo y estrés hídrico. La demanda hídrica estimada para la fase de floración fue de 2,50, 2,62 y 1,30 L m^2 $día^{-1}$ para áreas con 1, 2 y 3 años de cultivo, respectivamente. **Conclusiones.** Las estimaciones basadas en el NDVI capturaron eficazmente los requerimientos hídricos y el vigor vegetativo en diferentes edades de cultivo, revelando que el área de mayor antigüedad presenta una menor demanda hídrica asociada a un elevado estrés hídrico. Dada la ausencia de valores específicos para las etapas fenológicas de la pimienta negra, estos parámetros estimados constituyen una base fundamental para el perfeccionamiento del manejo del riego en el noreste de Pará.

Palabras clave: teledetección, coeficiente de cultivo, agricultura de precisión, riego.

Introduction

Black pepper (*Piper nigrum* L.) is one of the most commercialized spices in the world; it plays an important role in the agricultural economy of several tropical regions. In Brazil, its production is mostly concentrated in the North region, especially in the states of Pará and Amapá, where it represents an important source of income for small and medium-sized producers (Ambrozim et al., 2021). The cultivation of this crop requires careful management, especially regarding water availability, since both excess and scarcity of water can compromise plant development, productivity, and quality of the final product.

In the face of climate change and growing scarcity of water resources, the efficient use of water in agriculture has become one of the main challenges to ensure the sustainability of production systems. Irrigation, when properly managed, can mitigate the effects of climate variability and ensure the stability of agricultural production, even under adverse conditions. It is estimated that about 304 million hectares are irrigated in the world, which demonstrates the relevance of this practice in tackling global food insecurity (Dibaba et al., 2020; Malek et al., 2018).

In Brazil, the adoption of irrigation technologies has allowed for more efficient use of the productive potential of agricultural areas, contributing to increased productivity and crop resilience during periods of drought (Bernardi et al., 2015). However, irrigation represents the sector that consumes the most water on the planet, accounting for approximately 70 % of freshwater abstraction on a global scale (Qin et al., 2019). This scenario imposes pressures on water resources, especially in developing countries, where access to water may be limited and infrastructure still lacks adequate investments (Çetin et al., 2024; Yadav et al., 2022).

To ensure a rational management of irrigation, it is essential to know the crop evapotranspiration (ETc), a parameter that represents the plant's water demand and can be estimated from the reference evapotranspiration (ETo) and the crop coefficient (Kc) (Dingre & Gorantiwar, 2020). Precision in determining Kc is essential, as this value varies according to the species, the phenological phase of the crop, and the local climatic conditions (Alves et al., 2017; Doorenbos & Pruitt, 1977).

The determination of these variables is usually time-consuming and requires great experimental effort, which makes it difficult to access essential information for efficient irrigation management of the main crops. The classical

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method for estimating reference evapotranspiration (ETo) is based on modeling using the Penman-Monteith equation (Allen et al., 1998; Allen et al., 2005), which considers local climatological variables. It is also possible to estimate crop evapotranspiration (ETc) by direct methods, such as lysimeter weighing, which allows observing the variation in soil moisture where the crop is planted (Schneider et al., 1998). With the ETo and ETc values obtained by direct methods, the crop coefficient (Kc) can be determined using the ratio between these two variables, as described by Allen et al. (1998).

As an alternative, indirect methods have been developed with the help of remote sensors and geotechnology tools, which enable the monitoring of vegetation through spectral indices. Among the most used indices are the NDVI (Normalized Difference Vegetation Index), the SAVI (Soil-Adjusted Vegetation Index), and the VARI (Atmospherically Resistant Vegetation Index), which are efficient in estimating vegetative vigor and spatial variability of crop biomass (Marcial-Pablo et al., 2021; Shao et al., 2021). These technologies offer a promising approach to estimate Kc in a dynamic, spatialized, and less expensive way, especially in regions with scarce meteorological data.

Despite the relevance of the black pepper crop for the Brazilian economy, particularly in the North region, there is still a lack of studies aimed at defining technical parameters for the management of irrigation of this crop. The absence of specific Kc values for the different phenological phases makes it difficult to properly design irrigation systems, which can result in water waste or plant water stress. This study aims to estimate the water demand of black pepper (*Piper nigrum* L.) during the flowering phase in the Northeast region of Pará, by means of satellite images to obtain the NDVI and, from it, the estimation of the crop coefficient (Kc).

Materials and methods

Study area

The black pepper cultivation areas used in the research are located in the Avelinos community, 18 km from the municipal seat of Santa Luzia do Pará, in the state of Pará, Brazil. The cultivation area is positioned at the following geographic coordinates: latitudes 1°24'57.37" S and 1°24'54.17" S; longitudes 47°01'25" W and 47°01'22" W (Figure 1). The climate of the region is characterized as type Am, according to the Köppen-Geiger classification, with average annual temperatures between 26.0 °C and 27.0 °C and average annual rainfall of 2,522.6 mm.

The soils of the region are classified as dystrophic Yellow Latosols, with high acidity, high levels of Fe and Al oxides, and low natural fertility, typical characteristics of the Amazon region (Santos et al., 2018). The studied property has an area of 2 hectares cultivated with black pepper (*Piper nigrum* L.) cultivar Singapore. The cultivation is divided into different stages of development (1, 2, and 3 years), grown without the use of irrigation throughout the cycles.

Data collection

Initially, the geographic positioning of the study area was identified by collecting the geographic coordinates of the black pepper cultivation areas using a Garmin GPS device (GPSMAP 62sc) and downloading satellite images. Images captured on May 31, 2018, re-ferring to orbit point 222/061 of the Landsat 8 satellite, OLI sensor, with a spatial resolution of 30 × 30 m and a temporal resolution of 16 days, available on the Earth Explorer platform of the United States Geological Survey (s. f.) were used. The images were processed by converting digital numbers (DN) into physical values.

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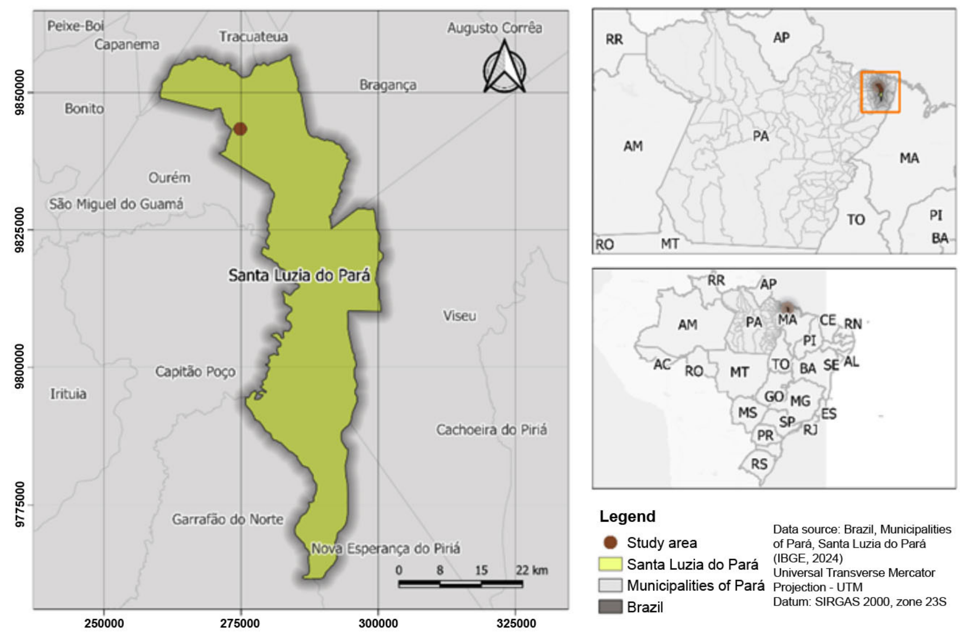

Figure 1. Area cultivated with black pepper in the municipality of Santa Luzia do Pará, state of Pará, Brazil, with an experiment conducted from 2016 to 2018 in plots with 1, 2, and 3 years of cultivation, corresponding to the years 2016, 2017, and 2018, respectively.

Figura 1. Área cultivada con pimienta negra en el municipio de Santa Luzia do Pará, estado de Pará, Brasil, con un experimento realizado de 2016 a 2018 en parcelas con 1, 2 y 3 años de cultivo, correspondientes a los años 2016, 2017 y 2018, respectivamente.

The SAFER model requires physical parameters derived from satellite remote sensing and reference evapotranspiration estimates obtained from meteorological station data (Safre et al., 2022). Therefore, standard methodological procedures were performed to obtain the following parameters: net radiation, net longwave radiation, planetary albedo, surface albedo, latent and sensible heat fluxes, Normalized Difference Vegetation Index (NDVI), soil heat flux, and surface temperature. A schematic flowchart of the steps for ET estimation using the SAFER algorithm is presented below.

Atmospheric correction was performed using radiometric conversion of bands 4 and 5 of the Landsat-8 satellite. To minimize atmospheric effects, the DOS (Dark Object Subtraction) method was applied, as described by Chávez (1988). The images were then processed using Quantum GIS (QGIS) software, version 2.14.9, developed by the Open Source Geospatial Foundation (OSGeo).

In the radiometric conversion process, digital numbers (DN) are transformed into irradiance values (Equation 1) and subsequently into reflectance (Equation 2), according to the methodology described by Teixeira et al. (2015).

$$L\lambda = M_L \times Q_{Cal} + A_L \tag{1}$$

Where: $L\lambda$ is the top-of-atmosphere (TOA) spectral radiance (W m^{-2} sr^{-1} µm^{-1}); M_L is the band-specific multiplicative rescaling factor from the metadata file; A_L is the band-specific additive rescaling factor (offset) from the metadata; and Q_{Cal} represents the quantized and calibrated standard product pixel values (DN). The gain and offset compensation values are provided in the image metadata file.

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$$\rho\lambda = \frac{\pi \times L_\lambda \times d^2}{ESUN_\lambda \times CosZ} \quad (2)$$

Where: $\varrho\lambda$ is the planetary top-of-atmosphere (TOA) reflectance (dimensionless); $ESUN_\lambda$ is the mean solar exoatmospheric irradiance for each band (W m^{-2} µm^{-1}); Z is the solar zenith angle (radians); and d is the Earth-Sun distance in astronomical units (AU).

To calculate the surface albedo (αs) (Equation 3), the required parameters were determined using the planetary albedo equation, with the weights proposed by Teixeira et al. (2017).

$$\alpha s = 0.6054 \times \propto top + 0.0797 \quad (3)$$

Surface temperature (*Ts*) was obtained through the residual method (Andrade et al., 2020) based on the radiation balance equation (Equation 4):

$$Ts = \frac{G_R - \alpha_0 G_R + \varepsilon_a T_a{}^4 - Rn}{\varepsilon_s \sigma} \quad (4)$$

Where: G_R is the daily incident global solar radiation (W m^{-2}); T_a is the average air temperature (K); and R_n is the daily net radiation (W m^{-2}). The atmospheric (ε_a) and surface (ε_s) emissivities were defined based on Equations 5 and 6, respectively, and σ is the Stefan-Boltzmann constant (5.6704 × 10^{-8} W m^{-2} K^{-4}).

$$\varepsilon_a = a_A\ (-h\ t)^{bA} \quad (5)$$

$$\varepsilon_s = a_S\ h\ NDVI + b_s \quad (6)$$

Where: t is the atmospheric transmissivity to incident radiation at the top of the atmosphere; *NDVI* is the Normalized Difference Vegetation Index; and a_S, b_S, a_A, and b_A are regression coefficients equal to 0.06, 1.00, 0.94, and 0.10, respectively, according to Teixeira (2010) and Teixeira et al. (2015).

The net radiation (Rn) was calculated using Equation 7:

$$Rn = H + LE + G \quad (7)$$

Where: *H* is the sensible heat flux (W m^{-2}); *LE* is the latent heat flux of evaporation (W m^{-2}); and *G* is the soil heat flux (W m^{-2}), which was determined using Equation 8, as proposed by Bastiaanssen (2000).

$$G = [Ts\ (0.0038 \propto + 0.0074 \propto) \times (1 - 0.98\ NDVI4)]\ Rn \quad (8)$$

Where: *Ts* is the surface temperature (°C); α is the surface albedo; and *Rn* is the net radiation (W m^{-2}).

The sensible heat flux (H) was calculated using Equation 9, as shown below:

$$H = \frac{\rho \times C_P \times dT}{R_{ah}} \quad (9)$$

Where: ϱ is the air density; C_p is the specific heat of air at constant pressure (1004 Jkg^{-1}K^{-1}); *dT* is the temperature difference (T1 – T2) between two heights (Z1 and Z2); and R_{ah} is the aerodynamic resistance to heat transport (s m^{-1}).

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To obtain the latent heat flux *LE* (W m^{-2}), the mass flux in the atmosphere resulting from the evapotranspiration (ET) process is considered. It is calculated as the residual of the energy balance between net radiation *Rn* (W m^{-2}), soil heat flux G (W m^{-2}), and sensible heat flux *H* (Equation 10):

$$LE = Rn - G - H \quad (10)$$

Where: *Rn* is the net radiation (W m^{-2}); *G* is the soil heat flux (W m^{-2}); and *H* is the sensible heat flux (W m^{-2}).

NDVI, Kc, and ETc of black pepper

For the determination of ETc, it is necessary to obtain the black pepper Kc beforehand. The Kc was estimated based on the NDVI obtained from satellite images. The NDVI is a spectral index of vegetation ranging from −1 to 1, indicating the vegetative state of plants: values close to −1 represent critical vegetative conditions, while values close to 1 indicate vegetation with optimal vigor. This index is calculated based on the difference between the reflectances of the bands in the near infrared (ϱ5) and red (ϱ4), divided by the sum of these same reflectances (Freden et al., 1974), and is expressed in Equation 11.

$$NDVI = \frac{\rho 5 - \rho 4}{\rho 5 + \rho 5} \quad (11)$$

Where: *ϱ5* is the reflectance of the near-infrared band, and *ϱ4* is the reflectance of the red band.

Following the acquisition of surface albedo *(αs)*, surface temperature *(Ts)*, *NDVI*, and *ETo* calculated via the Penman-Monteith method, the study proceeded to determine the instantaneous ratio ET/ETo (Kc). This ratio was estimated using the Simple Algorithm for Retrieving Evapotranspiration (SAFER), which uses biophysical parameters derived from satellite imagery. According to Teixeira (2010), Equation 12 was used for this estimate.

$$\frac{ET}{ETo} = \exp\left[a + b\left(\frac{Ts}{\alpha s * NDVI}\right)\right] \quad (12)$$

Where: *ET* is the actual evapotranspiration (mm day^{-1}); *ETo* is the reference evapotranspiration (mm day^{-1}); *a* and *b* are the regression coefficients, with values of 1.0 and −0.008, respectively; *To* is the surface temperature (K); α*s* is the surface albedo (dimensionless); and *NDVI* is the Normalized Difference Vegetation Index (dimensionless).

Reference evapotranspiration (ETo) was calculated using the FAO standard method via Ref-ET software (Allen, 2016), which provides standardized algorithms for estimation based on user-provided meteorological data. These input data were obtained from the National Institute of Meteorology (INMET) station nearest to the study site and included air temperature, atmospheric pressure, actual vapor pressure, soil heat flux, net solar radiation, and wind speed. While Ref-ET supports multiple input units and results are generated in mm h^{-1}, these values were subsequently integrated into Excel spreadsheets to obtain results in mm day^{-1}.

The daily Eto was estimated at 4.3 mm day^{-1}, which is representative of the study area, because when site-specific data are unavailable, data from a nearby station with similar climatic and geographic characteristics can be reliably used for estimation (Allen et al., 1998). *ETc*, which represents the effective water consumption by the crop, was calculated as the product of the estimated *Kc* and *ETo*. This calculation followed the method proposed by Albuquerque & Maeno (2007), as shown in Equation 13.

$$ETc = Kc \times ETo \quad (13)$$

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Results

NDVI values determined from orbital sensor images

The NDVI of the black pepper crop, referring to the phenological stage observed during the image capture period used for its determination, ranged from 0.44 to 0.77 in the areas with 1 and 2 years of cultivation, and from 0.33 to 0.44 in the area with 3 years of cultivation (Figure 2A). The Kc estimated from NDVI for the crop's flowering stage in the studied region was 0.61, 0.64, and 0.30 for crops with 1, 2, and 3 years, respectively (Figure 2). These results indicate that the 3-year-old cultivation area lacks active vegetation cover due to the low vegetative vigor of the plants.

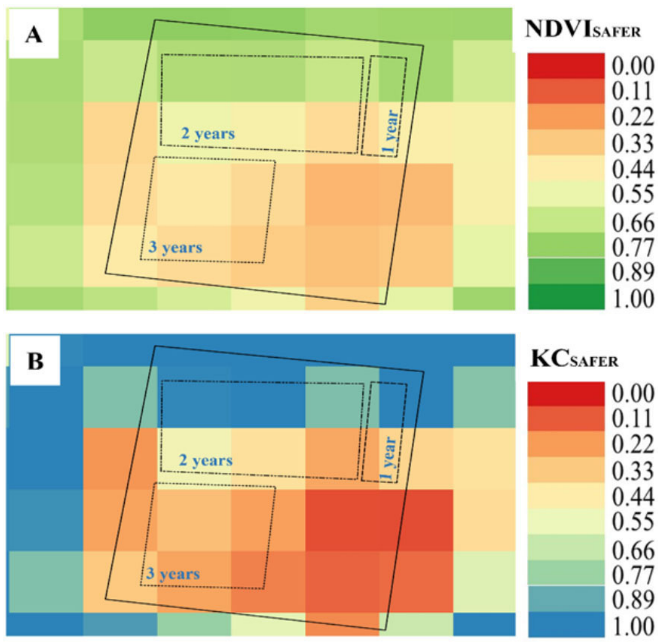

Figure 2. A) Normalized Difference Vegetation Index (NDVI) values for areas with 1, 2, and 3 years of cultivation, corresponding to the years 2016, 2017, and 2018, respectively, located in the municipality of Santa Luzia do Pará, state of Pará, Brazil. **B)** Crop coefficient (Kc) values estimated from NDVI for the black pepper crop at the flowering stage in the same region.

Figura 2. A) Valores del índice de vegetación de diferencia normalizada (NDVI) para áreas con 1, 2 y 3 años de cultivo, correspondientes a los años 2016, 2017 y 2018, respectivamente, ubicadas en el municipio de Santa Luzia do Pará, estado de Pará, Brasil. **B)** Valores del coeficiente de cultivo (Kc) estimados a partir del NDVI para el cultivo de pimienta negra en la etapa de floración en la misma región.

Based on the Kc values estimated in this study and considering that the average ETo of the region during the analyzed period was 4.3 mm day^{-1}, the average ETc values for black pepper were 2.50, 2.62, and 1.29 mm day^{-1} for areas with 1-, 2-, and 3-year-old cultivation, respectively. The average behavior of NDVI, Kc, and ETc in the three cultivation areas showed similar trends. NDVI behaved similarly in the 1- and 2-year-old crops, both with an average value of 0.55, while in the 3-year-old cropping system, the value was 0.33, indicating low vegetative vigor of the plants (Figure 3A).

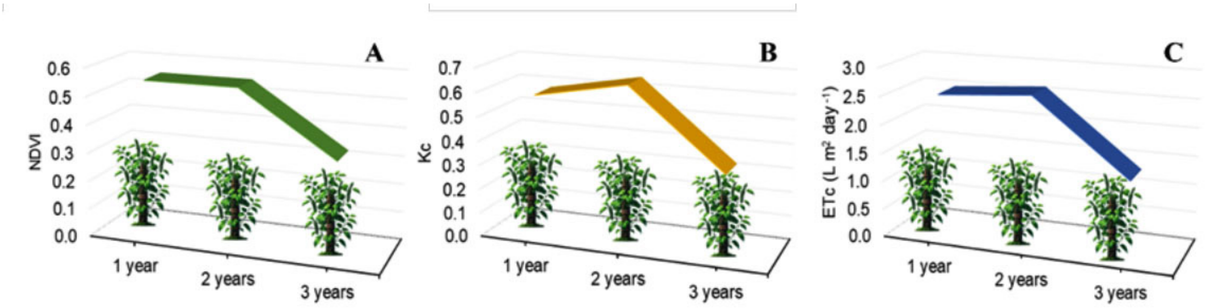

Figure 3. A) Normalized Difference Vegetation Index (NDVI) values for areas with 1, 2, and 3 years of cultivation, corresponding to the years 2016, 2017, and 2018, respectively, located in the municipality of Santa Luzia do Pará, state of Pará, Brazil. **B)** Estimated crop coefficient (Kc) values from NDVI for black pepper crops in the flowering phase. **C)** Crop evapotranspiration (ETc) values (L m^2 day^{-1}) for crops with 1, 2, and 3 years of implementation.

Figura 3. A) Valores del índice de vegetación de diferencia normalizada (NDVI) para áreas con 1, 2 y 3 años de cultivo, correspondientes a los años 2016, 2017 y 2018, respectivamente, ubicadas en el municipio de Santa Luzia do Pará, estado de Pará, Brasil. **B)** Valores del coeficiente de cultivo (Kc) estimados a partir del NDVI para cultivos de pimienta negra en fase de floración. **C)** Valores de evapotranspiración de los cultivos (ETc) (L m^2 $día^{-1}$) para cultivos con 1, 2 y 3 años de implementación.

The values of Kc and ETc were similar in the 1- and 2-year-old crops (Kc = 0.61 and 0.64; ETc = 2.50 and 2.60 mm day^{-1}, respectively), although the 1-year-old system had slightly lower means than the 2-year-old system (Figures 3B and 3C). Conversely, the 3-year-old crop presented significantly lower mean values for these parameters (Kc = 0.30; ETc = 1.29 mm day^{-1}), reflecting a compromised physiological and vegetative state, which indicates critical water and nutritional status (Figures 3B and 3C).

Discussion

Understanding the vegetative dynamics of black pepper at different cultivation stages is essential to accurately estimate its water demand, especially during critical phases such as flowering. The results obtained in this study demonstrate significant variations in the values of NDVI, Kc, and ETc between black pepper cultivation systems with different ages, which reflects differences in the vegetative vigor and water demand of the plants. The greater the soil cover or leaf area developed, the greater the surface area available for solar photon absorption and subsequent conversion of this energy into evapotranspiration, as previously demonstrated by Pereira et al. (2020).

In general, monitoring vegetation index variability enables the estimation of key crop parameters such as growth rates, the evaluation of management practices (Maia et al., 2023), and the identification of environmental impacts on yield potential (Albornoz et al., 2019). Specifically, NDVI facilitates the early detection of anomalies, including pest infestations, diseases, or physiological decline (Lasaponara et al., 2024). Lower NDVI values reflect reduced biomass density or plant stress (Larrea-Gomez et al., 2024), serving as a proxy for overall vegetation health and potential mortality (Puteh et al., 2020).

In black pepper cultivation, NDVI is used to assess vegetation health by measuring the reflectance difference between the near-infrared and red bands. High NDVI values correlate with a significant presence of healthy, photosynthetically active vegetation (Hu & Dong, 2018; Lasaponara et al., 2024). In the 3-year-old crop, NDVI values near zero were observed, indicating low vegetative vigor and sparse canopy density, which aligns with field observations. According to Feng et al. (2016), the spectral reflectance of the plant canopy is influenced by soil type, canopy density and width, and biophysical properties—factors directly related to ground cover, a variable that exhibited significant variation among the studied cultivation areas.

Areas with lower vegetation cover tend to have a higher rate of direct soil evaporation, which reduces the availability of water for plants. In terms of water balance, the water available in the soil for the crop depends directly on the balance between precipitation and evapotranspiration. A clear understanding of how evapotranspiration is regulated by abiotic and biotic factors is essential to assess the impact of water on ecosystem productivity (Scott et al., 2021). The authors point out that increased water availability tends to favor transpiration to a greater extent than evaporation.

The low vegetative vigor in the 3-year-old cultivation system may be linked to water deficit, as the crops are rainfed. At this stage, the crop is in full production, undergoing physiological wear after harvest and restarting the cycle with flowering and fruiting, phases that typically demand high levels of water and nutrients. Although the 3-year-old crop was in a phenological stage of high theoretical demand, the indices did not confirm such elevated water requirements. They remained low due to foliar senescence, which reduced transpiration. This condition was validated by both NDVI data and in situ observations.

In northern Brazil, the post-harvest phase of the Singapore black pepper cultivar coincides with the period of lower annual rainfall. This highlights the importance of understanding the crop's water needs and applying adequate irrigation for recovery and survival. Failure to supply sufficient water after the harvest period compromises plant vigor, causing critical vegetative conditions at the start of a new reproductive cycle, as seen in 3-year-old cultivation areas.

On the date of acquisition of the orbital images, the crop was in the flowering phase, which typically requires peak water supply; therefore, Kc values were expected to be near 1.0, as this coefficient represents the ratio between specific crop evapotranspiration and ETo. The values found for the 1- and 2-year-old crops are in accordance with the physiology of the plants in this period. However, the 3-year-old system presented lower than expected values, which can be explained by the yellowing of the plants, associated with nutritional and water deficiency, since fertilization had not yet been carried out and the system did not have irrigation, being subject to the water stress typical of the less rainy period.

Flowering is the phase of greatest water demand for black pepper, which makes knowledge of ETc essential for the accurate calculation of the crop's water demand. Evapotranspiration estimates by remote sensing offer great potential to support sustainable water management strategies. It should be noted that, as in several other crops, the productivity of black pepper can be severely limited by water scarcity. Accurate information about plant growth status and soil water availability is critical for efficient irrigation management.

The application of an irrigation depth compatible with the demand of the crop during flowering favors greater flower emission, bunch formation, and fruit development, leading to increased productivity and income for the producer. Adequate water availability contributes directly to floral development and grain filling (Passioura & Angus, 2010). On the other hand, water stress impairs seed formation and reduces the total mass per plant. Periods of drought can negatively affect floral characteristics and pollinator attraction, compromising the reproductive success of the crop (Rering et al., 2020). Drought is responsible for more annual losses than all pathogens combined, directly affecting plant physiology, promoting early flowering, stunted growth, and decreased productivity (Gupta et al., 2020).

In the Amazon region, there are two distinct climatic periods: one rainier and the other with less precipitation. Therefore, it is essential to define Kc values through remote sensing studies adapted to these two periods. Because of the limitations of the orbital platforms regarding data accuracy, it is recommended to carry out complementary studies using terrestrial platforms, which offer better spatial and temporal resolution, allowing a more accurate analysis of small cultivation areas and greater proximity to the real values of Kc. This enables more accurate and efficient irrigation calculations.

Continuous monitoring of ET, especially in irrigated agricultural areas, becomes increasingly relevant in the face of climate change (Volk et al., 2024), intense droughts and fires, and pressures on water resources caused by human activities, such as excessive water extraction for supply and agriculture. These factors have severely impacted water availability, which has resulted in greater competition for this resource worldwide (Rallo et al., 2021). Such a scenario can lead to reallocations in the use of water in agriculture, prioritizing crops with higher added value and socioeconomic relevance, such as soybeans, cocoa, açaí, corn, cotton, rice, and beans (Passioura & Angus, 2010), which meet the growing global demand for food.

Conclusions

NDVI values derived from Landsat 8 imagery satisfactorily represented the vegetative status of the black pepper crop. The Kc estimated from NDVI accurately reflected crop water requirements, showing consistency with the vegetative vigor observed in the field. Young crops (1 and 2 years old) exhibited higher vigor and water demands (2.50 and 2.62 mm day^{-1}), whereas the 3-year-old crop showed a critical vegetative state and lower water demand (1.30 L m^2 day^{-1}), requiring closer attention to water management. Given the lack of specific coefficients for the crop's phenological stages, remote sensing demonstrates high potential for irrigation management; therefore, the proposed values serve as essential tools for efficient irrigation management in Northeastern Pará.

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Conflict of interest

The authors declare no conflict of interest.

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