

# Evapotranspiration and the crop coefficients of black bean (*Phaseolus vulgaris*) with weighing lysimeters in a subtropical region

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**Abstract.** Gil-Marín JA, Zermeño-González A, Córdova-Rodríguez MX, Ramírez-Rodríguez H, Melendres-Alvarez AI, Moreno LS, Khamkure S. 2025. Evapotranspiration and the crop coefficients of black bean (*Phaseolus vulgaris* L.) with weighing lysimeters. *Asian J Agric* 9: 349-357. The water needs of a crop depend on the weather conditions, crop characteristics, and stage of development, which are represented by the crop coefficient (Kc), whose values change throughout the crop's stages of development. This understanding is the result of a meticulous research process, ensuring the reliability of these findings; knowing the crop evapotranspiration is essential to improving water use efficiency. This study aimed to determine the values of the crop evapotranspiration (ETc) and Kc for a black bean crop using a weighing lysimeter under greenhouse conditions. The research was conducted in the greenhouse of the graduate program in Tropical Agriculture at the University of Oriente (UDO), located on the Juanico Campus in Maturín, Monagas State, Venezuela, during the dry season from March to June 2020, on an Ultisol soil. The results showed that the bean's daily rate of evapotranspiration (ETc) was 3.16, 6.31, 8.37, and 4.80 mm day<sup>-1</sup> for the initial growth, vegetative, flowering, and maturity stages, respectively. The evapotranspiration for the complete growing cycle was 458.31 mm, corresponding to a water volume of 4,583.10 m<sup>3</sup> ha<sup>-1</sup>. The crop coefficient (Kc) for each development stage was 0.51 for the initial stage (10 days), 0.88 for the vegetative stages (35 days), 1.20 for the flowering stage (20 days), and 0.85 for the maturity stage (8 days).

**Keywords:** FAO-56 method, reference evapotranspiration, subtropical region, weighing lysimeter

**Abbreviations:** ETc: Crop evapotranspiration, ETr: Reference crop evapotranspiration, Kc: Crop coefficients

## INTRODUCTION

Within the group of legumes, *Phaseolus vulgaris* L. is one of the most important species worldwide, serving as a valuable source of proteins and other essential nutrients for human nutrition (Flores et al. 2024; Santella Quintero et al. 2024). In this sense, Herrera et al. (2024) assert that, in addition to its carbohydrate and mineral content, it is considered the primary source of vegetable proteins. It is cultivated practically everywhere in the world, with production reported in 129 countries across five continents. Latin America is the region of greatest production and consumption. It is estimated that more than 45% of the world's production comes from this region, where it is considered one of the basic products of the peasant economy.

Beans are a staple food in the Venezuelan diet. It is grown in almost all states of the country, with a significant percentage of cultivated areas corresponding to small and medium growers (León-Brito et al. 2019; León-Brito et al. 2020; Palacios Chávez 2023). According to MAC (2015), in 2014, Venezuela had a production volume of 7,578 tons, a harvested area of 9,939 ha, and an average yield of 762 kg ha<sup>-1</sup>. For 2015, production was 8,479 tons, with a harvested

area of 11,969 ha and a mean yield of 708 kg ha<sup>-1</sup>. In 2022, 1,47814 hectares of rain-fed agriculture were harvested, yielding a total production of 120,900 tons with an average yield of 0.818 tons per hectare (FAOSTAT 2024). Currently, Venezuela's total bean production is insufficient to meet the growing population's demand and the impact of climate change on crop yields (Domínguez-Suárez et al. 2019; Medina et al. 2019).

Of the total agricultural surface area planted in Venezuela, 45% corresponds to the cultivation of the bean crop. Beans are consumed as dried grains that are exclusively for human consumption and are considered a strategic food, constituting, together with corn, a staple of the Venezuelan diet. Beans provide approximately one-fifth of the total protein consumed by the population (Sanchez et al. 2018; Ekmeiro-Salvador and Arévalo-Vera 2023). Currently, our country's production of legumes, specifically black beans (*P. vulgaris*), is significantly reduced (Flores et al. 2016; León-Brito et al. 2018). The cultivation of black beans remains highly profitable despite widespread poor irrigation practices and a lack of research to determine the effect of environmental factors on the water demand of this crop. When the amount of water a plant consumes is unknown, it is challenging to implement effective irrigation planning.

Therefore, developing an appropriate methodological procedure to quantify the water requirements of bean plant growth in greenhouses remains highly relevant due to its effects on improving production profitability. Water application should respond to a dynamic that depends on the conditions where the crop is established, the plant's phenological stage, and the type of substrate or soil used for the plant's growth. By determining the crops' evapotranspiration in an agricultural region, it is possible to implement efficient irrigation management, thereby optimizing the use of the area's water resources (Pereira et al. 2015; Padilla-Valenzuela et al. 2023; Ramezani et al. 2025). Crop evapotranspiration encompasses two key processes: soil surface evaporation and transpiration from the plant's leaves (Allen et al. 2006; Daniel et al. 2020). A crop's evapotranspiration rate can be obtained by direct field measurements or estimated using meteorological data. In any case, the required data must be obtained directly from the agricultural areas. As the surface increases, the solution becomes more demanding. The methods for measuring the evapotranspiration rate of a crop can provide better information on the different aspects of crop management that affect the rate of plant transpiration.

The crop coefficients ( $K_c$ ) are the relation between the actual crop evapotranspiration ( $ET_c$ ) and the reference evapotranspiration ( $ET_r$ ). The  $ET_c$  corresponds to the evapotranspiration rate of a large green vegetation area with full soil surface cover, with no restrictions on soil water availability (Allen et al. 2006). The values of  $ET_c$  across the different growth stages of a crop can be determined by measuring the rate of  $ET_c$  under open-field conditions and by measuring the difference in soil water content throughout the crop cycle at various time intervals.  $ET_c$  values can also be obtained by using weighing lysimeters. Previous studies (Nicolás-Cuevas et al. 2020; Al Tamimi et al. 2022; Negash et al. 2024) have demonstrated that precise measurements of  $ET_c$  and the corresponding  $K_c$  for various crops can be obtained using weighing lysimeters; given the hypothesis that weighing lysimeters can be used in

greenhouse conditions to obtain precise values of plants' evapotranspiration rates and crop coefficients. The objective of this study was to determine the evapotranspiration rate of black bean plants (cv. Tui Tui) and the corresponding crop coefficients at different stages of plant development, growing in a greenhouse.

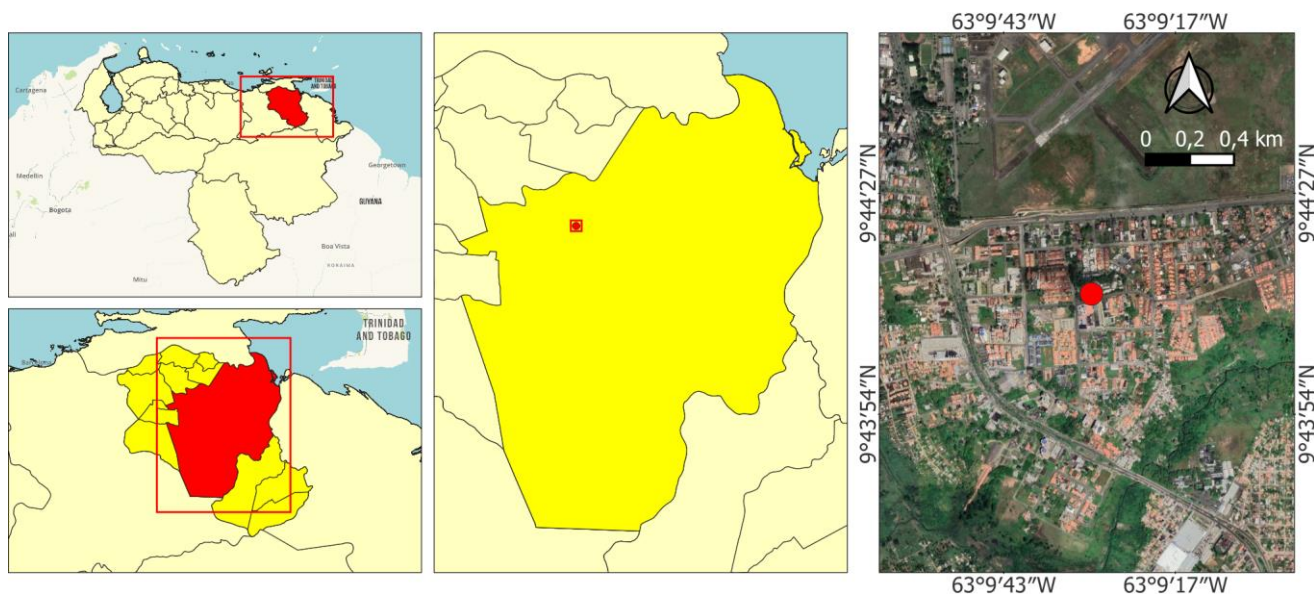
## MATERIALS AND METHODS

### Study area

This research was carried out in greenhouse No. 2 of the Postgraduate Program in Tropical Agriculture of the University of Orient (UDO), located on the Juanico Campus, Maturín, Monagas state, Venezuela, located at about 60 m asl., with a geographic location between  $9^{\circ}44'12''$  N and  $63^{\circ}09'24''$  W (Figure 1). According to the meteorological station of the Venezuelan Air Force (FAV), the area has an average annual temperature between 22 and 27°C, characterized by a rainy tropical savannah climate with a distinct dry season, accompanied by very fluctuating annual rainfall, ranging from 966 mm to 1,743 mm (Gil-Marín et al. 2023).

### Procedures

The evapotranspiration rate of the plants (black beans, cv. Tui Tui, native to Brazil) was determined by gravimetric measurements in pots, which involved successive weighing with intermediate irrigation applications and precise drainage measurements to obtain the water content. The water evapotranspired by the plants was then calculated by the difference in the water content. The work was conducted in pots made of plastic containers 25.60 cm in diameter and 35 cm in height, with a volume of 18 L. For the study, 60 containers were filled with soil (sandy loam texture) from the Sabana Experimental Station of the Universidad de Oriente. The physical and chemical properties of the soil are shown in Tables 1 and 2.



**Figure 1.** Research location in Juanico Campus, Maturín, Monagas, Venezuela

**Table 1.** Particle content, bulk density, and soil porosity of the soil used in the study

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm <sup>-3</sup> )	Particles density (g cm <sup>-3</sup> )	Porosity (%)	Depth (cm)
0 - 20	74.8	11.2	14.0	1.46	2.58	44.0	1.5
20 - 50	70.0	4.10	21.6	1.20	2.54	53.0	6.2
50 - 100	64.0	10.4	25.6	1.23	2.26	48.0	7.4

Note: Source: Hossne (2015)

**Table 2.** Physical properties and electrical conductivity of the soil used in the study

Depth (cm)	FC (%)	WP (%)	AW (%)	Water content (%) for each tension value (kPa)				EC (dS/m)	OM (%)
				33	100	500	1000		
0 - 20	10.9	5.1	5.8	8.9	8.3	6.5	5.8	0.25	1.37
20 - 50	14.7	6.2	8.5	12.5	10.6	8.9	7.2	0.14	0.84
50 - 100	11.0	5.3	5.7	9.6	8.6	7.6	6.0	0.188	0.50

Note: Source: Hossne (2015). FC: Field Capacity, WP: Permanent Wilting Point, AW: Available Water, EC: Electrical Conductivity, OM: Organic Matter

Hence, to have the same mass of soil for a fixed volume of 18 L of each pot, the following equation was used:

$$M_s = V * \rho_b$$

Where,  $M_s$  is the mass of dry soil,  $\rho_b$  is the soil bulk density, and  $V$  is the soil volume in the pot. Each pot was filled with a three-centimeter-thick layer of sifted gravel, followed by a calculated mass of soil, 25 kg, to a height of 28 cm and a volume of 18 L. Holes were made at the bottom of each pot to allow excess water drainage. The percolated water was measured using a 500 mL container.

The crop evapotranspiration rate (ETc) from each pot was calculated using the water balance equation:

$$ET_c = LI - LD + LR \pm \Delta LS$$

Where,  $LI$  is the irrigation depth,  $LD$  is the drainage depth,  $LR$  is the rain depth, and  $\Delta LS$  is the change in soil water depth.  $\Delta LS$  was obtained using the following equation:

$$\Delta LS = L_{s1} - L_{s2}$$

Where,  $L_{s1}$  is the soil water depth at the initial time (usually the water depth corresponding to field capacity), and  $L_{s2}$  is the soil water depth after a specific segment of time.  $L_{s2}$  was calculated with the following equation:

$$L_{s2} = (\theta_{w1} - \theta_{w2}) * \rho_{f*} * \rho_b$$

Where,  $\theta_{w1}$  is the soil water content (g/g) at the initial time, and  $\theta_{w2}$  is the soil water content (g/g) after the same time segment.

When using a weighing lysimeter,  $\Delta LS$  can be obtained as:

$$\Delta LS = (W1 - W2)/AL$$

Where,  $W1$  is the weight of the lysimeter at the initial time,  $W2$  is the weight of the lysimeter after the same time segment, and  $AL$  is the transversal section area of the lysimeter (633.47 cm<sup>2</sup>).

For time segments with no irrigation, no drainage, and no rain, the ET is calculated as:

$$ET_c = \Delta LS$$

The weight of the lysimeter at field capacity was determined by over-saturating the soil in the plots and allowing free drainage until a steady weight was observed (28.70 kg). A digital electronic scale with a 60 kg capacity and 20 g precision was used to measure the weight of the pots. A difference of 1 kg in the pots corresponded to a water depth of 19.44 mm. The weighing of the pots was made daily, and irrigation application to the pots was suspended when 80 percent of the fruits reached physiological maturity. The calibration of the lysimeters (containers with soil and plants) involved daily checks to ensure that the digital weighing balance provided accurate readings using known weights.

The crop coefficient ( $K_c$ ) values for the different stages of development of the black bean crop were calculated from the crop evapotranspiration data (ETc) obtained by weighing lysimeters, and the monthly reference evapotranspiration data (Etr) calculated using the Penman-Monteith equation using the Cropwat 8.0 program (Allen et al. 2006).  $K_c$  was determined using the following equation:

$$K_c = ET_c/E_{tr}$$

For this study, four development stages were considered for the bean plants: initial stage (from seeding to seedling emergence); vegetative (from seedling emergence to first open flowers); flowering (from first open flowers to beginning of pod formation); maturity (from beginning of pod formation to beginning of leaves yellowing and dropping) (Madriz et al. 2013; Pérez et al. 2019; Mago et al. 2021). The FAO Penman-Monteith method (Allen et al. 2006) is considered the standard and most recommended method for determining reference evapotranspiration under different climatic conditions. This method requires weather variables such as net radiation, air temperature, relative humidity, wind speed, and canopy resistance of the vegetated surface. The Hargreaves-Samani method (Ferreira et al. 2020) was also employed in this study

to determine the reference or potential evapotranspiration; this method is more straightforward, requiring only daily solar radiation and the average air temperature. A linear regression analysis was done between  $ET_c$  and the reference evapotranspiration ( $ET_r$ ) estimated by the Hargreaves-Samani and Penman-Monteith methods.

The evapotranspiration and  $K_c$  values at each stage of the plant's development were calculated as the average of 60 measurements, obtained from 60 containers (25.6 cm in diameter and 35 cm in height) with 25 kg of sandy loam soil and a bean plant, serving as weighing lysimeters. The plants' evapotranspiration was measured daily.

## RESULTS AND DISCUSSION

The black bean cv. Tui-Tui's growing cycle throughout the four stages of development was 73 days (Table 3). The vegetative and flowering stages accounted for 75.3% of the total cycle, with flowering being the shortest stage.

The initial stage spans from the day of sowing until the plants cover approximately 10% of the soil surface. The vegetative stage covers the period from the end of the initial stage until the plants reach full foliage growth, and the flowering stage initiates. The flowering stage encompasses the transition from the vegetative stage to the start of grain maturity, denoted by the yellowing of the plant leaves and the development of a brown color in the grain. The maturity stage spans from the end of the flowering stage to the complete senescence of the plant (harvest).

### Plant's evapotranspiration rate ( $ET_c$ )

The plant's evapotranspiration rate ( $ET_c$ ) exhibited an upward trend from the initial stage (sowing) of the crop to the flowering stage, and then decreased in the maturity stage (Table 4). At the initial stage,  $ET_c$  was low ( $3.16 \text{ mm day}^{-1}$ ) because the plants had begun to develop, and the water had mostly evaporated from the soil surface. In the vegetative stage, the leaves of the plants increased in size, and the daily  $ET_c$  also rose ( $6.31$ ). At the flowering stage, the plants exhibited full foliage growth, and the water requirements for grain formation increased, resulting in the highest  $ET_c$  rate ( $8.37 \text{ mm day}^{-1}$ ). The plant leaves initiate senescence during maturity, and the  $ET_c$  was reduced ( $4.80 \text{ mm day}^{-1}$ ). The difference in  $ET_c$  rate at each stage of development was also influenced by climate variation in the greenhouse, including solar radiation, air temperature, and relative humidity.

Previous studies have shown that bean plants are susceptible to excess soil humidity and water deficit (Nigussie

et al. 2024). The highest  $ET_c$  was observed at the flowering and pod formation stage, which coincides with the report of Rivera and Chaves (2019), who reported that the flowering stage has the highest water demand for bean plants. do Nascimento et al. (2024) observed maximum  $ET_c$  values of  $15.2 \text{ mm day}^{-1}$  in greenhouse conditions for mung beans in the flowering and pod-filling stages. Similarly, de Queiroz et al. (2024) reported  $ET_c$  values of  $10.6 \text{ mm day}^{-1}$  for the same type of bean; in both cases, the  $ET_c$  values were higher than those observed in this study. For field conditions, the crop bean  $ET_c$  in the flowering and pod-formation stages had the highest value of  $3.98 \text{ mm day}^{-1}$  (Rodríguez-Correa et al. 2023). According to Bhattacharya (2020), when the water supply is insufficient to meet the crop's needs during the flowering and pod-filling stages, grain yields decrease drastically. The availability of soil moisture during the reproductive stage is crucial for the grain yield of bean plants (Hernandez et al. 2015). On the other hand, the water depth and the distribution of irrigation intervals affect crop yield when the phenological stages with the greatest water requirement (flowering and pod filling) are not considered, as well as losses due to evapotranspiration, system efficiency, and the intrinsic characteristics of the soil based on overall fertility (Lekgoathi et al. 2025).

The results of this work coincide with those reported by Domínguez-Suárez et al. (2016), who found similar responses when working with 64 lines of common beans under two soil moisture conditions. González-Cueto et al. (2017) also defined irrigation depth and scheduling based on the phenological stage of bean plant development. The grain yield of the bean plant depends on water availability during the flowering and pod-filling stages (López et al. 2011). The study by Fang et al. (2010) showed that the grain yield of a plant bean depends on the tolerance to low humidity conditions during the flowering stage. Depending on the duration and magnitude of the drought period, yield losses of 20 to 100% can occur in bean plants (Fabre et al. 2010).

**Table 3.** Growth stages of the black bean crop (*Phaseolus vulgaris*), cv. Tui-Tui grows in pots and a protected environment

Stage	Range		
	Start day	Final day	Duration
Initial growth	1	10	10
Vegetative	11	45	35
Flowering	46	65	20
Maturity	66	73	8

Note: Date of sowing: 22 March 2020

**Table 4.** The evapotranspiration rate of black bean plants was measured throughout the four stages of development in pots inside a greenhouse

Stage of development	Duration (days)	Evapotranspiration rate			
		$\text{mm stage}^{-1}$	$\text{mm day}^{-1}$	$\text{m}^3 \text{ha}^{-1} \text{stage}^{-1}$	$\text{L plant}^{-1} \text{stage}^{-1}$
Initial growth	10	31.57	3.16	31.6	2.00
Vegetative	35	221.01	6.31	63.1	14.01
Flowering	20	167.33	8.37	83.7	10.60
maturity	8	38.39	4.80	48.0	2.43

Full cycle	73	458.31	5.66	226.4	29.04
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The ETc of the whole crop cycle (73 days) was 458.31 mm, corresponding to 4583.08 m<sup>3</sup> ha<sup>-1</sup> and an average of 5.66 mm day<sup>-1</sup>. The plant water consumption for the whole cycle was 29.04 L plant<sup>-1</sup> under greenhouse conditions (Table 4). Jabow et al. (2015) reported that for the initial stage of development, the ETc of common bean plants was 32 mm, a value similar to the one obtained in our work. For open-field conditions and drip irrigation, the ETc of a black bean crop was 187 mm, a value significantly lower than the one obtained in this study (Escobar et al. 2014). However, Moreno et al. (2014), also in open-field and drip irrigation, reported an ETc of 491 mm for a black crop bean, similar to the ETc found in our study. Ortiz et al. (2010) reported evapotranspiration values of 327 mm in 2008 and 350 mm in 2009 for the black bean crop during an 85-day crop cycle, which are lower than those observed in this work. Escalante-Estrada et al. (2001) reported a fluctuating ETc of 292 mm to 406 mm for a black bean crop during the summer season. In Mexico, the ETc for the entire growing cycle of the black bean cultivar Rocha was 217.94 mm, 45.7% smaller than the ETc value reported in our study (Díaz-López et al. 2023).

#### Relation between ETc obtained by lysimetric measurements and the estimated ETr by two methods

The crop evapotranspiration (ETc) obtained through lysimetric measurements was compared with the reference evapotranspiration calculated using the Hargreaves-Samani method (ETr H-S) and the Penman-Monteith method (ETr

P-M). The ETc for the crop's whole season was significantly higher (51.15%) than ETr H-S but very similar to ETr P-M, only 3.27% higher (Table 5), indicating the possibility of using the Penman-Monteith method for estimating the black bean crop evapotranspiration under greenhouse conditions.

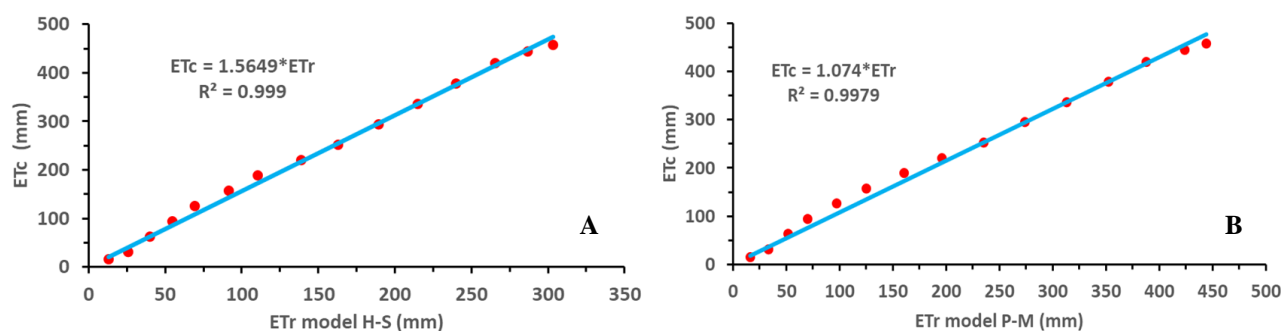
The study by Pire and Rodriguez (2009) also found a slight difference between the ETc of a black bean crop and the ETr calculated using the Penman-Monteith method (4%). The Penman-Monteith equation has been reported in several studies as the method that best reproduces the reference evapotranspiration under various climatic conditions (Gaafer et al. 2024; Ippolito et al. 2024; Liu et al. 2024). The ETc of an onion crop obtained by lysimetric measurements (525 mm) was higher than the ETr calculated by the Hargreaves-Samani equation (429 mm), corresponding to a difference of 22.38% (García et al. 2013).

A linear regression between the accumulated crop evapotranspiration obtained by lysimetric measurements (ETc) and the reference evapotranspiration estimated by the Hargreaves-Samani method (ETr H-S) for the whole crop season showed that ETc was underestimated by 56.49% when using the Hargreaves-Samani method (Figure 2). However, the linear regression between the ETc and the reference evapotranspiration estimated by the FAO Penman-Monteith method (ETc P-M) demonstrated that ETc was only underestimated by 7.4% if the Penman-Monteith method is used to calculate the reference evapotranspiration (Figure 2).

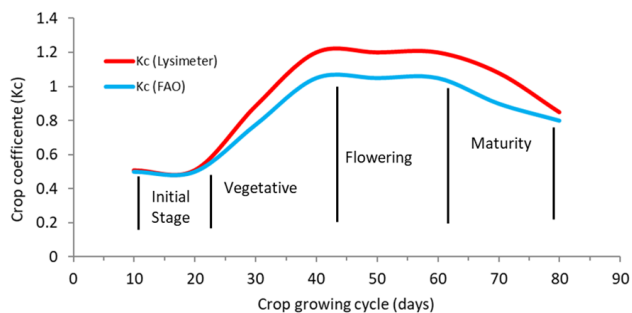
**Table 5.** Measured evapotranspiration rate (ETc) of the black bean crop (*Phaseolus vulgaris*) cv. Tui-Tui, grown in pots inside a greenhouse, and estimated reference evapotranspiration calculated with the Hargreaves-Samani method (ETr H-S), and the Penman-Monteith method (ETr P-M)

Days	0 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to 30	31 to 35	36 to 40	41 to 45	46 to 50	51 to 55	56 to 60	61 to 65	66 to 70	71 to 73
ETc	15.79	31.6	63.14	94.72	126	157.9	189.44	221	252.6	294	336.2	378.07	419.9	443.9	458.3
ETr H-S	12.85	25.7	39.9	54.7	69.2	91.7	110.2	139	162.7	190	214.8	240	265.25	286.9	303.2
ETr P-M	16.5	33	51.5	70	97.5	125	160.5	196	235	274	313	352	388	424	443.8

Note: ETc, ETr-H-S, ETr P-M are accumulated values of evapotranspiration in mm



**Figure 2.** Correlation between the black bean evapotranspiration (ETc) obtained by lysimetric measurements and the reference evapotranspiration (ETr) calculated by the methods of Hargreaves-Samani (A) and Penman-Monteith (B)



**Figure 3.** Theoretical Kc values (FAO) from Allen et al. (2006) and the actual values obtained in the crop of black beans (Kc Lysimeter) grown in pots inside a greenhouse

**Table 6.** Reference evapotranspiration (ET<sub>r</sub>) obtained by the FAO-56 method, crop evapotranspiration (ET<sub>c</sub>) obtained by lysimetric measurements, and the crop coefficients (K<sub>c</sub>) for each stage of development of the black bean crop (*Phaseolus vulgaris*) variety Tui-Tui, grown in pots inside a greenhouse

Phases	Duration (days)	ET <sub>r</sub> (mm day <sup>-1</sup> )	ET <sub>c</sub> (mm day <sup>-1</sup> )	K <sub>c</sub>
Initial stage	10	6.19	3.16	0.51
Vegetative	35	7.18	6.31	0.88
Flowering	20	7	8.37	1.20
Maturity	8	5.62	4.80	0.85

The determination coefficient between the accumulated values of ET<sub>c</sub> and ET<sub>r</sub> H-S was 0.999, and between ET<sub>c</sub> and ET<sub>r</sub> P-M was 0.998 (Figure 2). This result indicates that both models can be used to estimate ET<sub>c</sub>, but the accumulated ET<sub>r</sub> must be multiplied by the coefficient 1.5694 when using the H-S model. Still, if the P-M model is applied, the accumulated ET<sub>r</sub> has to be multiplied by the coefficient 7.4. García et al. (2013) also reported a high coefficient of determination between the ET<sub>c</sub> of a black bean crop measured by a lysimeter and the ET<sub>r</sub> calculated by the Hargreaves-Samani method (0.995) and between ET<sub>c</sub> and ET<sub>r</sub> calculated by the Penman-Monteith method (0.997). The high correlation between accumulated ET<sub>c</sub> and ET<sub>r</sub> values indicates consistency under the evaluated conditions. However, ET<sub>r</sub> values were lower than the ET<sub>c</sub>. A drainage lysimeter measured the coefficient of determination between the Chinese bean crop ET<sub>c</sub>.

### K<sub>c</sub> coefficients of the black bean crop under greenhouse conditions

The average crop coefficient grows from the initial stage of development to the flowering stage and then decreases in the maturity stage (Table 6); the same pattern was observed in the average daily crop evapotranspiration (ET<sub>c</sub>) and the Penman-Monteith reference evapotranspiration (ET<sub>r</sub>) (Table 6). The increase in K<sub>c</sub> values from the initial stage of development to the flowering stage was due to the growth of the plants' leaves and roots. In the flowering stage, the plant's photosynthetic activity increases due to the photosynthates required for flower and pod growth and

filling; therefore, the plant needs to maintain open stomata, and the crop reaches its highest rate of ET<sub>c</sub> (8.37 mm day<sup>-1</sup>) and the highest K<sub>c</sub> (1.2). In the maturity stage, the plant water requirements are reduced because the plant leaves initiate senescence and fruit ripening; consequently, the rate of ET<sub>c</sub> decreases to 4.80 mm day<sup>-1</sup> and the K<sub>c</sub> to 0.85 (Table 6).

The FAO crop coefficient (K<sub>c</sub> FAO) (Allen et al. 2006) was very similar to the crop coefficient obtained by the lysimetric measurements of crop evapotranspiration (K<sub>c</sub> Lysimeter) during the initial stage of development (Figure 3). As the vegetative stage develops, the K<sub>c</sub> (Lysimeter) value is higher than the K<sub>c</sub> (FAO) value. Throughout the vegetative, flowering, and maturity stages, the K<sub>c</sub> (Lysimeter) value is higher than the K<sub>c</sub> (FAO) value. By the end of the maturity stage, both K<sub>c</sub> are approximately equal (Figure 3). During the flowering stage of development, the highest K<sub>c</sub> (Lysimeter) values were approximately 1.20 and 1.05 for the K<sub>c</sub> (FAO) (Figure 3). Although this difference is slight, to improve the water use efficiency in the irrigation applications for this crop, it is suggested that K<sub>c</sub> values be generated at the agricultural surface where the crop will be established. Additionally, when using the K<sub>c</sub> values generated for a particular crop and location, a more accurate determination of the crop evapotranspiration is obtained, leading to the highest crop yield.

The K<sub>c</sub> values obtained by measuring evapotranspiration of a bean crop using a drainage lysimeter in open-field conditions were 0.45, 0.88, 1.28, and 0.75 at the initial, vegetative, flowering, and maturity stages, respectively (Chavarria Parraga et al. 2019). While under greenhouse conditions with drainage lysimeters, Hermoso Veramendi et al. (2024) reported crop coefficients of 0.412 in the initial stage, 0.904 during development, 1.058 in the middle of the season, and 0.804 at the end, with a total vegetative period of 94 days, in both cases the K<sub>c</sub> values are similar to the ones obtained in our work. However, the study by Nascimiento et al. (2024) on mung beans, which measured crop evapotranspiration in open-field conditions, reported K<sub>c</sub> values of 0.73, 1.24, 1.86, and 1.32, which are higher than the values obtained in this study. Another study by El-Noemani et al. (2015) found values ranging from 0.63 to 0.64 for the initial stage, 0.87 to 0.82 for development, 0.99 to 1.09 for midseason, and 0.80 to 0.95 for the harvesting stage in the case of the Bronco variety.

As the black crop bean variety Tui Tui used in our study exhibited rapid and significant leaf growth, covering the total pot area 35 days after sowing, the plants had a high transpiration rate, and the K<sub>c</sub> values were greater than the theoretical K<sub>c</sub> values (Allen et al. 2006). The weather conditions within the greenhouse also influenced our study's evapotranspiration and K<sub>c</sub> values, as the incident solar radiation, temperature, relative humidity, and wind speed may differ from those outside the greenhouse. Another factor that could have affected the K<sub>c</sub> and evapotranspiration values was the soil texture, as soil surface evaporation is related to soil texture. Additionally, the soil water availability for plants depends on the hydraulic properties of the soil, which are related to the soil texture (Bonet Pérez et al. 2010; Sevostianova et al. 2025). The K<sub>c</sub> values are affected

by different factors, including differences in plant morphology, which affect light interception and aerodynamic resistance; the distribution and responses of stomata to the environment; the irrigation system and its effect on soil moisture distribution; irrigation frequency and rainfall; interception of dew and condensation that affects canopy resistance (Kullberg et al. 2017; Jamshidi et al. 2020; Pereira et al. 2021; Kebede et al. 2025). On the other hand, Seidel et al. (2019) also point to bean sowing dates as another factor that influenced the Kc curves due to varying growth rates and growth durations. Crop coefficients are inherent characteristics of the crop that are used to calculate crop evapotranspiration or water requirements (ETc) (Chandra and Kumari 2021). The presented Kc curves can help farmers make accurate estimates of daily irrigation water demand during the season, as well as over the long term, under local conditions.

### Crop production

The yield of a particular crop is the result of agronomic crop management, including fertilization, pest control, irrigation, and the interaction of the plants with environmental variables such as solar radiation, air temperature, humidity, and wind speed. The average grain yield per plant obtained in our study was 30 g. For a seeding of 30 cm between plants and 80 cm between furrows corresponds to a plant density of 41667 plants/ha and a yield of 1,200 kg ha<sup>-1</sup>. Although our study was conducted in plots in a controlled environment, we aimed to compare the results obtained in this study with those reported for the growth of this and other bean cultivars in open-field conditions. The yield of a black bean crop grown in open-field conditions in a semi-arid region of Turkey was 1,213 kg ha<sup>-1</sup> (Yavuz 2021), which is similar to the yield obtained in our study; however, the yield of the black bean crop cv. Tacarigua grown in the open field in Lara state, Venezuela, was 2,623 kg ha<sup>-1</sup>, which is twice the yield found in our study (Escobar et al. 2014). The survey by Lozada (1997) reported a yield of 2,693 kg ha<sup>-1</sup> of the black bean cv. Ica-Pijao in Lara State, Venezuela, under open-field cultivation. In another study, Valderrama et al. (1997) obtained a yield of 2,290 kg ha<sup>-1</sup> of the black bean crop variety Ana-133 in the state of Auraca, Venezuela, also in open-field cultivation. It seems that the yield of the black bean crop cv. Tui Tui is inferior to other black bean crop varieties, or, under greenhouse conditions, the yield of the Tui Tui cv. is smaller than that obtained in open-field cultivation. In the pinto bean cultivar Othello, Sharma and Rai (2022) reported yields of 3,825 kg ha<sup>-1</sup> in arid areas of Wyoming, United States, which are higher than those observed in this work. A study by Gradiz et al. (2025) with the Virgo bean cv. reported yields in a range of 1,200 to 4,100 Kg ha<sup>-1</sup> in Nebraska, USA.

Conclusions, the evapotranspiration (ETc) of the black bean crop cv. Tui Tui for the whole cycle (73 days) was 458.31 mm. This finding has practical implications for crop water management, as it guides the timing and amount of irrigation needed. The ETc increased from the initial to the flowering stage and decreased in the maturity stage, a pattern that can be directly applied to optimize water use.

The ETc of the vegetative and flowering stages accounted for 84.73% of the whole crop cycle, a key point for planning irrigation schedules. The crop coefficient (Kc) exhibited a similar trend, increasing from the initial to the flowering stage and then decreasing in the maturity stage. The highest Kc value was observed in the flowering stage with a value of 1.20, indicating that, in this stage, the crop evapotranspiration was higher than the reference evapotranspiration.

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