WATER REQUIREMENTS OF FLAX AND MODIFICATION OF THE CROP COEFFICIENT IN THE AGRO-PASTORAL ECOTONE OF CENTRAL INNER MONGOLIA, CHINA

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Abstract. To rapidly and accurately determine the water requirement (WR) and crop coefficient (K_c) of drip irrigated flax (*Linum usitatissimum* L.), we conducted an insufficient surface drip irrigation experiment and determined critical growth stages for ensuring an optimal flax yield Combined with meteorological data and crop water requirement measurements, the potential evapotranspiration (ET_0) of flax and actual K_c were calculated and compared with the K_c recommended by FAO Document 56. When flax was free from drought and at an optimal yield, the crop WR was 327.4 mm. The largest daily average WR intensity was the greatest in the budding–flowering period, in which a sufficient water supply is crucial. After modifying the K_c as recommended by the FAO, the K_c values were 0.21, 0.58, 0.85 and 0.44, in the intial, rapid, middle, and late growth stages, respectively. The K_c over the whole growth period was 0.59. When the flax irrigation quota of ground drip irrigation was 210 mm in the middle region of the Inner Mongolia agro-pastoral ecotone, China, the theoretical WR calculated by the single K_c method recommended by FAO 56 was 313.44 mm, 10% lower than the measured crop WR.
Keywords: *cultivation of oil crops, Northern foothills of Yinshan Mountain, pit positioning test, evapotranspiration, wetting ratio of drip irrigation, planned wet layer*

Introduction

The agro-pastoral ecotone of middle Inner Mongolia borders the Yinshan Mountains to the south, and the Mongolian Plateau to the north, which is an ecologically fragile zone. Due to the natural conditions, such as a dry and cold climate, poor soil, and relative lack of water in this area, the range of crops suitable for cultivation are limited. However, with optimal irrigation and fertilizer supply, a high yield of crops including flax, potato, wheat, oats, barley, or pea, could be obtained (Muhammad et al., 2012; Yang, 2014). In the arid region of northern China, as in the rest of the world, flax is an economically important

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crop for the production of oil (Silska et al., 2020), which is rich in local variety and resources (Yi et al., 2018), and as a crop, being a specialty in the agro-pastoral ecotone of central Inner Mongolia. It is clear that water absorption and utilization of flax is critical for physiological and biochemical reactions and is affected by insufficient water supply and decreased moisture availability in the soil (Fang and Xiong, 2015), thus effective improvement of the water utilization rate is an important mean of increasing flax yield (Zhang, 2019). Greenhouse experiments have been conducted on a variety of flax cultivars under four water potential gradients of 0, -0.4, -0.8 and -1.2 MPa, mimicking drought stress, and the most drought-tolerant varieties were obtained by testing the physiological characteristics of plants and seed germination processes (Wang et al., 2021). Insufficient water supplies in the early growth stage in flax plants not only affect seedlings, but also reduce the accumulation of final dry matter, even if the drought stress is eliminated (Deng et al., 2015; Wu et al., 2019a). Therefore, timely irrigation of flax is crucial (Rao et al., 1988). Water requirement (WR) tests in flax under different water conditions were conducted in Yuzhong, Gansu Province, located in the Loess Plateau in northwest China; results showed that the WR increased with increasing irrigation levels, while the proportion of planned moisture storage and effective rainfall comprising the total crop water consumption decreased (Cui et al., 2015a; Yan et al., 2017). Adequate fertilizer (Mohammadi et al., 2010; USDA, 2020; Li et al., 2021) and a permissive soil environment (Mohammad et al., 2017; Pan et al., 2020) are as important as water for the optimal growth of flax; appropriate agronomic measures, such as film mulching, drip irrigation, and intertillage, also contribute to high yields of flax (Allen et al., 1998; Wu et al., 2012; Konstantin et al., 2019; Wu et al., 2019b).

At present, there are two approaches for calculating crop water requirement: the first is to measure the crop WR in each growth stage using a water balance method, and the other is to calculate the actual crop WR by calculating the reference WR. The FAO56 method is widely accepted as adequate for calculating crop WR in agricultural settings (Allen et al., 1998). In this method, the single crop evapotranspiration (ET_0) and crop coefficient (K_c) are calculated. K_c is an important parameter for irrigation scheduling and water allocation. ET_0 is an important index reflecting the evapotranspiration of the atmospheric environment, which reflects the influence of different meteorological factors on crop WR. It can be multiplied by the K_c to calculate crop water requirement (ET_c), which is important for effectively developing and utilizing regional water resources (Biazar et al., 2019; Xiang et al., 2020), an essential part of agricultural water management and decision-making (Hengsdijk et al., 2005; Peng et al., 2017; Zhang et al., 2020).

Expected K_c values for different crops in different growth periods are given in FAO56. Given that the K_c is based on climate conditions and plant morphology, it must be verified and modified according to factors including plant variety, climate, water, and fertilizer (Garcia et al., 2013; Guerra et al., 2016). Previous breeding studies in sugar cane pre-sprouted plantlets (PSP) grown in a greenhouse showed that the K_c derived from ET_c was higher than the recommended reference value from FAO56 (1.00–1.02 versus 1.46–1.53, respectively) (Luís et al., 2019). However, when grown in a field, K_c over the whole growth period was decreased by 4–25.5% compared with the recommended value from FAO56 (Dingre et al., 2020). Based on the FAO56, Liu (2021) optimized the ET_0 calculation method in Altay, Xinjiang, and modified the K_c value via the measurement of crop water requirements (Liu, 2021). In addition to weighing lysimeters, modern techniques such as large aperture scintillometers and eddy covariance detectors are often

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used to measure crop water requirement and K_c and have been trialed in an experimental farm near Bologna, Italy (Ragab et al., 2017). In a corn field in Zhangye Oasis in arid desert areas of northwestern China, the vorticity correlation method has also been used to analyze how canopy evapotranspiration and K_c changed seasonally (Gu et al., 2020). In New Delhi, India, differences between the K_c value measured by weighing lysimeter and the value recommended by FAO56 have been identified. The K_c value recommended by FAO56 is suitable for use under specific climatic conditions; however, different plant varieties have their own unique patterns of crop water use and evapotranspiration, as has been demonstrated in maize (Abedinpour, 2015). As K_c is generally measured in a specific plot or field, application needs to be extended to larger scale irrigated areas (Da et al., 2017). In Rio de Janeiro, Brazil, a Time Domain Reflectometry (TDR) probe was installed at 0.15 and 0.30 m depths and water balance methods were applied to obtain potato water consumption and K_c values under organic management practices (De et al., 2013). Lysimeters can be divided into two types: weighing and non-weighing (Creutzfeldt et al., 2010). The weighing lysimeters test soil is packed in a specially designed steel structure container, which can measure evapotranspiration in a short period of time, with high accuracy and high cost, and is suitable for measuring small areas (Zhao et al., 2010). Non-weighing lysimeters, also known as drainage type lysimeters, by controlling the groundwater level, measuring the amount of compensation water, its installation and operation are simple, low cost, and widely used. The non-weighing lysimeters for irrigation test has a large area and is representative.

Crop water requirement is the main consumption of agricultural water, reducing crop water requirement is the key part to reduce agricultural water consumption. Based on Penman-monteith formula, crop coefficient method proposed by Food and Agriculture Organization of the United Nations is a method to calculate the actual water requirement of crops by reference to potential evapotranspiration (ET_0) and crop coefficient (K_c). Although crop coefficient method has been widely used in the farming-pastoral ecotone of Inner Mongolia for wheat, maize, sugar beet, potato, and other major food crops, however, few research on oil crops (flax and oil sunflower) with short growth period, and there is a lack of systematic and comprehensive research on the water requirement of main oil crops in the agro-pastoral ecotone by the method of single crop coefficient. In this study, we carried out an insufficient drip irrigation experiment in flax in a test pit and determined the actual crop WR and the key stages of flax under properly hydrated conditions. We also calculated the potential evapotranspiration and actual K_c of flax according to the FAO Penman–Monteith equation, as recommended in FAO56, and the single K_c method. From these measurements, we then calculated the WR of flax crop under subsurface drip irrigation in the agro-pastoral ecotone of middle Inner Mongolia, providing the basis for planning, and designing irrigation system.

Materials and Methods

Geographical Area

The coordinates of the area used in this research are 111° 12’ 23.803” E, 41° 21’ 4.488” N. It is in Halawusu Village, Hilamuren Town, Damao Banner, Baotou City, Inner Mongolia, in the middle of the Inner Mongolia Plateau (Shi et al., 2022).

It has a cold, temperate continental monsoon climate. The annual mean temperature is 3.2℃, and the mean and lowest temperatures in January are 15.3℃ and –35.7℃, respectively. The mean and highest temperatures in July were 19.6℃ and 35.9℃,

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respectively. The maximum depth of frozen soil is 2.68 m. The annual average sunshine duration is 3246 h, precipitation is 281 mm, evaporation is 2526 mm, annual humidity, and annual mean wind speed is 5.2 m/s. The number of days with gales exceeding 17 m/s is 68 d throughout the year.

The southern terrain of the research area is higher than the northern, inclining to the north. The south is low mountains and hills, the north is low hills, and the middle is high plain. The terrain is flat and open, with an average elevation of 1550 m. The groundwater in this area is relatively abundant. The lithology of the aquifer is mainly phreatic confined water in sandstone and sandy gravel. The thickness of the aquifer is 3–10 m, and the buried depth of groundwater is 2–5 m (Tang et al., 2020).

Materials

The flax cultivar used in the experiment was Jinya No.7, which has a good yield, high oil content, and high resistance to wilting disease, and its growth stages are described in *Table 1*. The plant height of this flax variety is about 68 cm, and 80% of the root system is distributed in the cultivation layer of 20-30 cm.

Table 1. *Description of growth stages in flax and their corresponding start and end times*

Growth Stage	Initially Proposed Growth Days	Planned Depth of Wetting Layer (cm)
Sowing–Emergence	15/5-20/5, 5 d	15
Emergence–Fir	21/5-10/6, 20 d	30
Fir–Budding	11/6-10/7, 30 d	30
Budding–Flowering	11/7-5/8, 25 d	45
Filling–Maturity	6/8-15/9， 40 d	45
Total	120 d	

In order to achieve large-scale and accurate crop water demand testing, this study conducted irrigation experiments using a non-weighing evapotranspiration system (including a canopy, measuring pit, irrigation system, underground observation room, and drainage system, as shown in *Figure 1*). The length, width, and depth of each measuring pit are 4.5 m, 2.2 m, and 1.8 m. The measuring pit adopts a brick concrete structure, and the inner surroundings and bottom are treated with anti-seepage measures. The top is covered by a canopy, and the deep leakage water at the bottom of each measuring pit can be collected through a bucket type leakage measurement device installed in the underground observation room.

Figure 1. *Measuring pits used for inadequate irrigation experiments*

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The soil in the measuring pit (*Fig. 1*) was the original soil in the study area. The soil bulk density was measured in layers before the soil was taken out. According to the bulk density, the disturbed soil was backfilled 20 cm/layers every after the test pit was built.

The soil type was light millet calcium soil, and the multi-year average soil nutrient content was 0.14% total N, 89 ppm available N, 0.12% total P, 5 ppm available P, 2.06% total K, 153 ppm available K, pH 8.31, 2.17% total salt, 0.99% organic matter content. In general, available N levels were medium, available P levels were lacking, available K levels were high, and the soil was alkaline (Organic matter content 0.99%) (*Table 2*).

Table 2. *Soil water characteristic indices and soil texture of the study area*

Particle size composition (%)			Soil Texture
Clay	**Powder**	**Sand**	
7.3	26.0	60.3	Sandy Loam
Bulk density (g/cm3)	**Saturated Moisture (%)**	**Field Capacity (%)**	**Wilting Coefficient (%)**
1.44	22.9	20.5	5.5

Experiment Design

The test was designed with four treatments administered by subsurface drip irrigation, as follows: severe water shortage (CKHM1, the moisture content of soil wetting layer was 60% of the field moisture capacity), moderate water shortage (CKHM2, the moisture content of soil wetting layer was 70% of the field moisture capacity), slight water shortage (CKHM3, the moisture content of soil wetting layer is 80% of the field moisture capacity), and no water shortage (CKHM4, the moisture content of soil wetting layer is 90% of the field moisture capacity), as illustrated in *Table 3*. Three replicates were performed for each treatment, and there were 12 sub plots (measuring 2 m x 5 m each). Irrigation was carried out once after sowing, 2–3 times during each growth stage, for a total of ten times over the whole growth period. The irrigation times were May 18, June 1, June 15, June 28, July 9, July 18, August 1, August 12, August 22, and September 6.

Table 3. *Treatment design*

Treatment	Name	Irrigation Quota Per Application (mm)	Irrigation Quota (mm)	Total Number of Irrigation Treatments
Severe Water Shortage	CKHM1	12	120	10
Moderate Water Shortage	CKHM2	15	150	10
Slight Water Shortage	CKHM3	18	180	10
No Water Shortage	CKHM4	21	210	10

The test plot was shallow plowed to a depth of 15 cm on 8 May 2021, and 1.69 t of decomposed organic cow and sheep manure was applied per hectare as a base fertilizer. Flax was sown on May 15 with a sowing rate of 33 kg/ha (about 2.25 million plants per hectare), 15 cm row spacing, and diamine fertilizer application (225 kg/ha). In the stem–budding flax stage, a top dressing of urea (50 kg/ha) was applied once. Harvest and yield were measured on 20 September.

Test Indices and Methods

Test indicators included meteorology, soil moisture and particle size, soil nutrients, crop growth, etc.

The Hobo meteorological station (Origin, USA) was used to obtain meteorological measurements over the whole growth stage of flax (*Fig. 2a*). These measurements include evaporation/rainfall, daily mean/maximum/minimum temperatures, relative humidity, wind speed at a height of 2 meters, sunshine duration, and solar radiation.

Figure 2. *(a)Weather station and (b) soil moisture observation system used in this study*

The main meteorological indicators from May 1st to September 30th are shown in *Figure 3*, with an average temperature of 17.03 °C, an average wind speed of 4.2 m/s, and a daily average relative humidity of 44.12%.

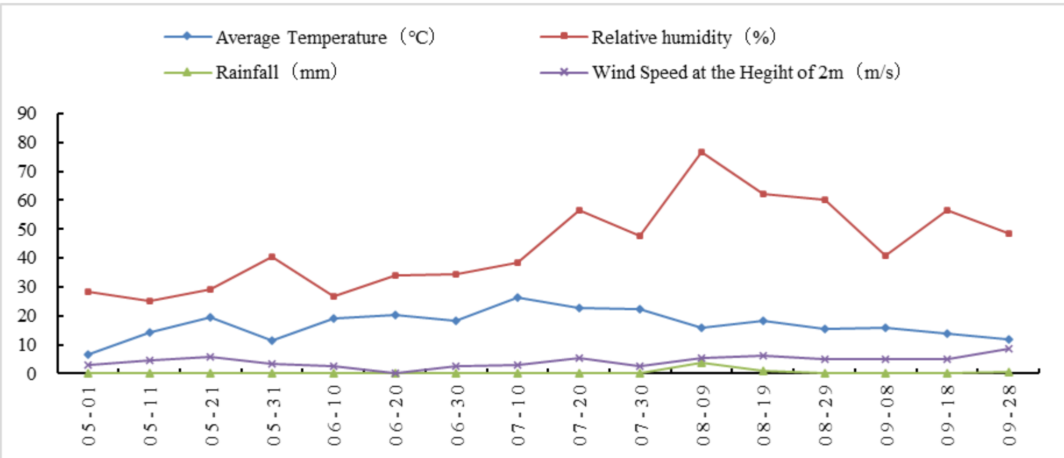

Figure 3. *Main meteorological indicators for the growth stage of flax (May 1-September 30)*

Existing sensors (EM50, Origin, USA, buried at depths of 20, 40, 60, 80, and 100 cm) were used to measure soil moisture, salinity, and temperature. Data were recorded every hour (*Fig. 2b*), but to ensure the reliability of these test data, they were collected once a week. The main soil moisture indicators from May 1st to September 30th are shown in *Figure 4*.

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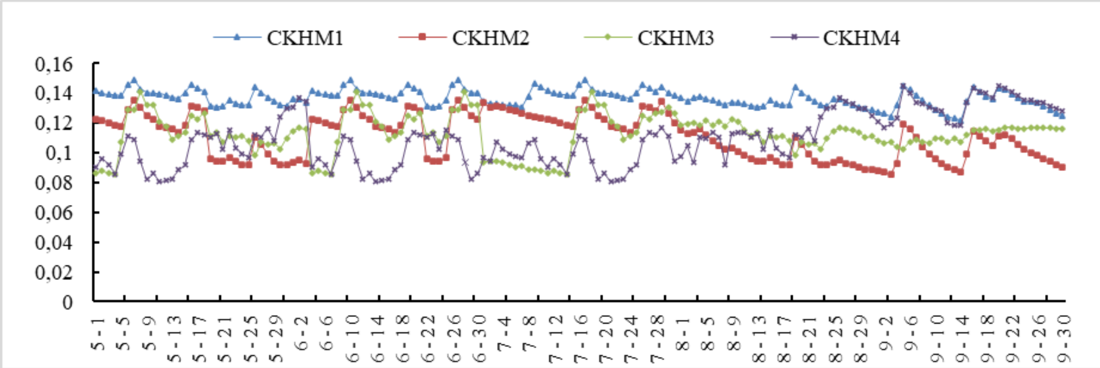

Figure 4. *Main soil moisture indicator for the growth stage of flax (May 1-September 30)*

The determination of soil mechanical components was carried out using a laser particle size analyzer (LS-609, Origin, USA). Soil chemical indices included total and available N content (determined using the Kjeldahl distillation method), total and available P content (determined using the sulfuric acid perchloric acid digestion method and sodium bicarbonate method, respectively), total and available K content (determined using the flame photometer, FP6410, Origin, China), and soil organic matter content (potassium dichromate volumetric method) (Bao, 2007).

Crop growth indicators included length of the vegetation period, main growth parameters, yield, etc. In this research, the cultivation time, sowing/emergence time, supplementary sowing/topdressing time, emergence rate, and the start and end time of each stage was recorded. Morphological indices were measured every seven days. After the flax had reached maturity, representative samples were randomly selected from the plot for yield measurement, which were each 1 m^2.

Data Analysis

The crop water requirement of naked oats in the irrigation test is calculated according to the water balance principle, as shown in *Equation 1*. The crop water requirement in the experiment can be calculated through the indicators such as naked oats irrigation amount, irrigation times, rainfall supply amount, and soil moisture.

$$ET_c = P_0 + K + M + W_t + \Delta W \quad \text{(Eq.1)}$$

In this equation, ET_c is crop water requirement (mm); P_0 is the effective rainfall during the growth period (mm); K is groundwater recharge (mm); M is irrigation water volume during growth period (mm); W_t is the change of soil water content caused by the increase or decrease of the soil wetting layer thickness at the beginning and end of each growth period, and the increase or decrease of soil water storage caused by the increase or decrease of soil wetting layer thickness. Since there is no increase or decrease of the soil wetting layer thickness, this item can be ignored; ΔW is the increase or decrease of soil available water supply caused by the change of soil water content at the beginning and end of each growth period, which is ignored in this study.

The calculation method for crop WR, the single K_c method, is shown in *Equation 2*. This considers both the actual WR of crops and the impact of meteorological factors on crop evapotranspiration. K_c combines the impact of crop characteristics and soil

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evaporation under standard climate conditions. K_c was transformed for use non-standard climate conditions according to corrections and equations in FAO56 (Liu, 2021).

$$ET_c = ET_0 \cdot K_c \quad \text{(Eq.2)}$$

In this equation, K_c refers crop coefficient of flax, and ET_c refers to the evapotranspiration (in mm) of crops in the absence of disease or pests, under optimal water and soil conditions, appropriate fertilization levels, and high yield in a large area under given climatic conditions. ET_0 is the reference crop evapotranspiration rate (in mm) without any water shortages.

Given the Penman–Monteith equation recommended in FAO56 (*Equation 3*) is based on conservation of energy and water vapor diffusion theory and takes account of meteorological factors and crop physiological characteristics, it is an internationally recognized equation used to calculate the potential evapotranspiration (ET_0) of crops, with reference to sufficient meteorological data (Liu, 2021).

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{(Eq.3)}$$

In this equation, R_n is net radiation; G is the soil heat flux; (e_s−e_a) is the water vapor pressure difference; Δ is the slope describing saturated vapor pressure as a function of temperature; γ is the hygrometer constant; and u_2 is wind speed at 2 m above the canopy.

Results

Field Measured Flax WR and its Pattern

Figure 5 and Figure 6 shows the WR and its model coefficient at each flax growth stage in water shortage treatment conditions. The WR was lowest in the seedling–fir stage, with a stage modulus coefficient of 18.15–8.66%, followed by the filling–maturity stage, with stage modulus coefficient of 18.86–19.18%; the highest WR and stage modulus coefficient were in the budding–flowering stage. The maximum stage modulus coefficient of CKHM1 was 32.80%, and the maximum water requirement in CKHM4 treatment in the budding–flowering stage was 104.87 mm.

In addition, the stage water requirements and stage modulus coefficients were closely related to not only the vigorous growth intensity of crops, but also the soil moisture. In a given stage, when the irrigation was high, WR and modulus coefficients were correspondingly high; conversely, when the irrigation was low, WR and modulus coefficients were correspondingly low. Therefore, between different water treatments, the WR and modulus coefficient of flax at different growth stages showed a certain change pattern.

Yield and Water Production Efficiency of Flax under Different Moisture Conditions

Table 4 shows the growth of flax under different treatments. In terms of fresh weight, CKHM3 (irrigation quota of 2400 m^3/ha) is the highest at 14700 kg/ha, higher than CKHM4 (irrigation quota of 2700 m^3/ha) at 800 kg/ha, higher than CKHM2 (irrigation quota of 1800 m^3/ha) at 4200 kg/ha, and higher than CKHM1 (irrigation quota of

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1500 m^3/ha) at 3700 kg/ha. Correspondingly, the yield of flax seeds is also the highest in CKHM3, at 3400 kg/ha, which is 100 kg/ha, 100 kg/ha, and 200 kg/ha higher than CKHM4, CKHM2, and CKHM1, respectively. In terms of the weight of sesame stalks, CKHM3 (5000 kg/ha) is higher than CKHM4 (4400 kg/ha), CKHM2 (4600 kg/ha), and CKHM1 (4400 kg/ha). In terms of plant height, CKHM4 (63.33 cm) is higher than CKHM3 (58.13 cm), CKHM2 (54.33 cm), and CKHM1 (53.20 cm). Chlorophyll is also higher than CKHM3 in the other three treatments, and in terms of basal stem and leaf area index, the flax does not show certain patterns with different irrigation amounts.

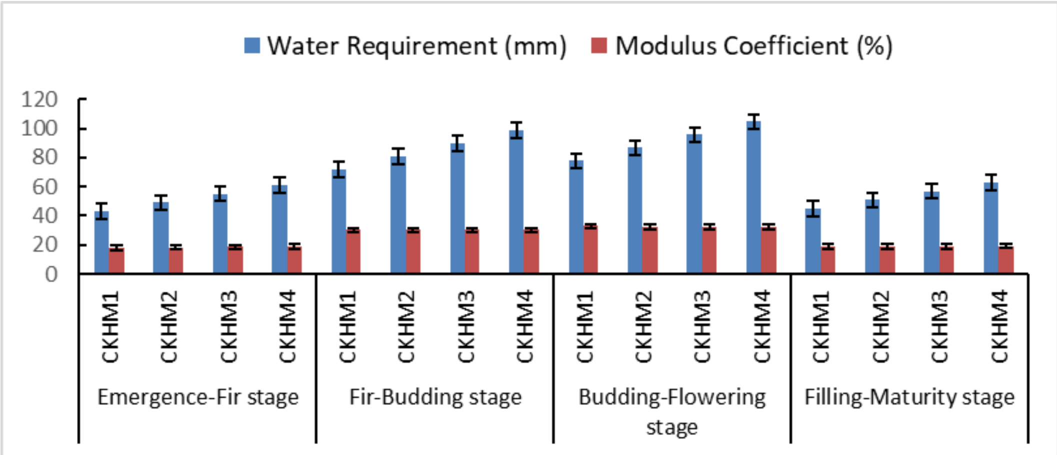

Figure 5. *Water requirements (WR) and modulus coefficients values in flax under different water shortage treatments*

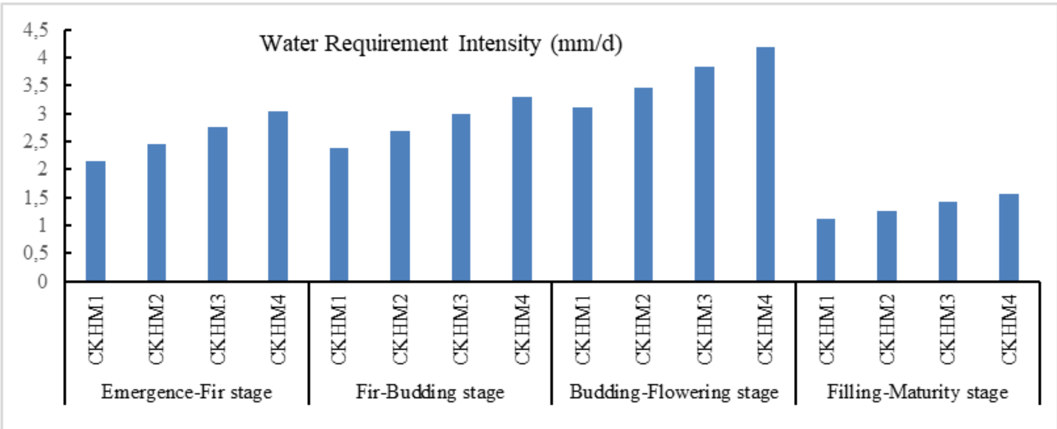

Figure 6. *WR intensity values in flax under different water shortage treatments*

Calculation of ET_0 in Growing Stage of Flax

The ET0 in the whole growth period of flax is 567.59 mm, as shown in *Fig. 7*, the maximum ET0 in later growth stage is 164.39 mm, the minimum ET0 in initial growth stage is 96.84 mm, and the growth stage average ET0 is 141.9 mm. The average daily ET0 of the whole growth period is 3.89 mm/d. Since the local average temperature in late May is only 3-6 °C and the flax is in the seedling stage, the ET0 during this period is relatively small, with an average of only 3.22 mm/d. With the gradual increase of air

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temperature and solar radiation, ET0 gradually increases after entering the bud flowering stage, and on middle of July reached the daily maximum ET0 6.9 mm/d. The minimum daily ET0 in the whole growth period occurs at the middle of September.

Table 4. *The growth of flax under different treatments*

Index	CKHM1	CKHM2	CKHM3	CKHM4
Fresh weight (kg/ha)	11000	10500	14700	13900
Yield of flax seed (kg/ ha)	3100	3300	3400	3300
Total of flax straw (kg/ ha)	4400	4600	5000	4400
Plant height (cm)	53.20	54.33	58.13	63.33
Basal stem (mm)	2.75	3.62	3.32	3.29
Leaf area index	3.46	3.27	3.08	2.96
Chlorophyll (mg/g)	1.91	2.28	2.87	2.68

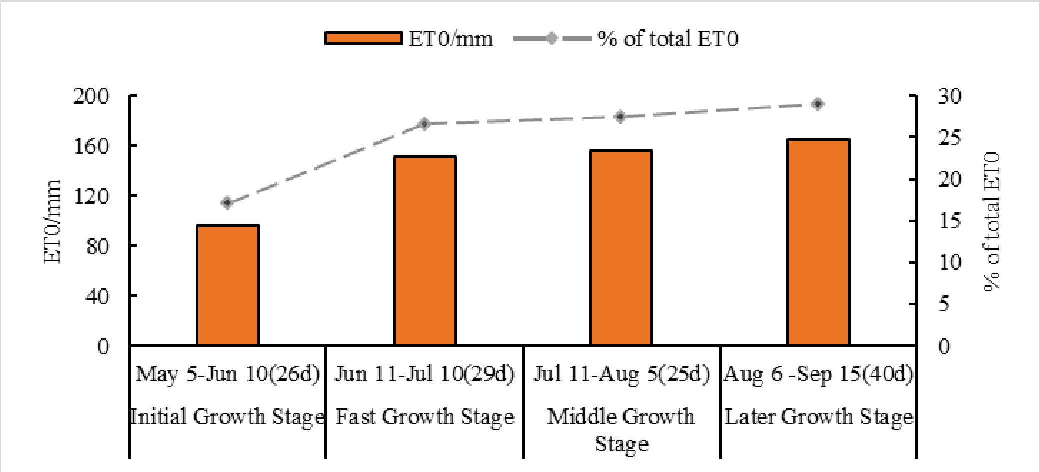

Figure 7. *Change in evapotranspiration (ET_0) during flax growth*

Preliminary Selection of Flax K_c

During flax growth, increases in plant height, canopy density, and leaf area, and soil evaporation and vegetation transpiration all affect K_c. According to the definition in FAO56, traditional crop growth stages need to be redivided.

According to the definition in FAO 56, the rapid growth period of flax starts when 10–15% of the ground is covered. When the ground is completely covered (the height of flax plants generally reaches the maximum at this point), the rapid growth period is complete (*Fig. 8*).

In the middle growth stage, the farmland is fully covered; the maximum plant height starts and ends at the mature stage. For flax, it generally ends at the filling stage. As flax is an oil crop, the flax seeds are harvested after completely grouting. Therefore, the late growth stage corresponds to grouting in this crop.

According to FAO 56, the K_{cini}, K_{cmid} and K_{cend} of flax are 0.35, 1.15 and 0.55 respectively in a standard environment (semi humid climate, minimum relative humidity of approximately 45%, wind speed of about 2 m/s at 2 m above the canopy) and standard planting conditions (without drought stress, high field management level).

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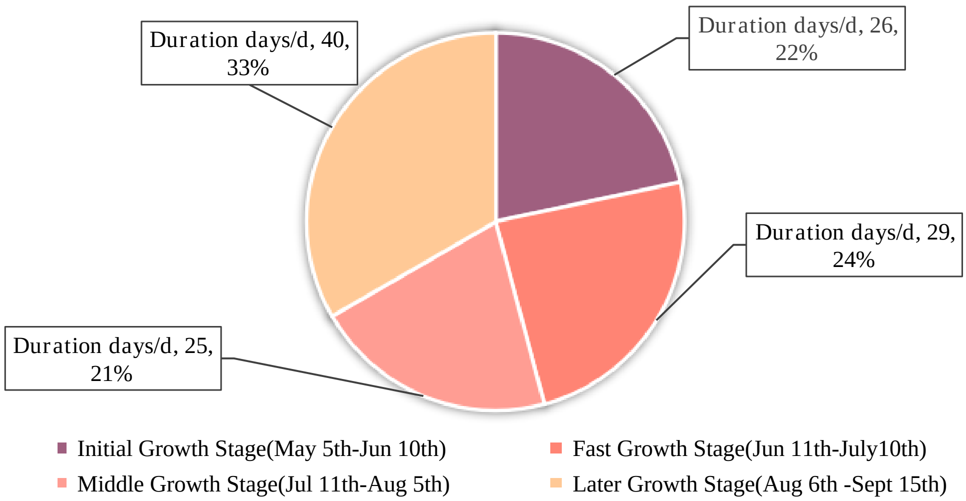

Figure 8. *Water requirement (WR) and WR intensity in flax under different water shortage treatments*

Modification of K_c Under the Single Crop Coefficient Method

K_c in the Initial Growth Stage (K_{cini})

According to FAO 56, when the average infiltration depth is 10–40 mm (once drip irrigation was conducted in the test area on 15 May, the irrigation quota is 24 mm), the K_{cini} at the initial growth stage of flax can be corrected using *Equation 4*.

$$K_{cini} = K_{cini(b)} + \frac{(I-10)}{(40-10)}\left[K_{cini(b)} - K_{cini(a)}\right] \quad \text{(Eq.4)}$$

where, in places with insufficient rainfall, the soil is kept moist through irrigation. Therefore, when the soil in the initial stages of growth was only moistened with rainfall, $K_{cini(a)}$ was obtained from the average K_{cini} in FAO56 when soil wetting intensity is from light to medium (3–10 mm each time), and $K_{cini(b)}$ could be obtained from the average K_{cini} at the initial stage of growth correlated with size of ET_0 and an irrigation interval greater than 40 mm. I represent the amount of irrigation in the test site, and the average infiltration depth (in mm). The K_{cini} value at the initial growth stage of flax under drip irrigation was found to be 0.3.

At the initial stage, K_{cini} was also limited by energy and water evapotranspiration (field capacity 20.5%, Wilting coefficient 5.5%), and it is also affected by the content of sand (60.3%) and clay (7.3%) in the soil. The K_{cini} of drip irrigation in flax at the initial growth stage was 0.21 after modified.

K_c in the Middle Growth Stage (K_{cmid})

The agro-pastoral ecotone of central Inner Mongolia has a dry climate and heavy sandstorms, which is not within the standard conditions included in FAO56 {in the semi humid climate zone, RH_{min} (the lowest average relative humidity in the middle growth period of flax) = 45%, u2 = 2m/s, no water stress, and high management levels}. For K_c in a non-standard state, FAO56 provides a modified K_{cmid} equation (*Equation 5*).

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$$K_{cmid} = K_{cmid(R)} + [0.04 \cdot (u_2 - 2) - 0.004 (RH_{min} - 45)] \cdot (\frac{h}{3})^{0.3} \quad \text{(Eq.5)}$$

$K_{cmid(R)}$ is the K_{cmid} in FAO56 during the middle growth stage of flax under standard conditions (1.15); u_2 is the wind speed at 2 m in the middle growth period of flax (m/s); RH_{min} is the lowest average relative humidity in the middle growth period of flax (%); and H is the actual average height of flax at this stage (m). The K_{cmid} of flax was 0.85 after modified.

K_c in the Late Growth Stage (K_{cend})

The K_{cend} of flax in FAO56 assumes a minimum relative humidity of approximately 45% and a wind speed of approximately 2.0 m/s at a height of 2 m. When the growth environment is different to this, the K_{cend} can be corrected according to actual meteorological factors (*Equation 6*).

$$K_{cend} = K_{cend(R)} + [0.04 \cdot (RH_{min} - 45) \cdot (\frac{h}{3})^{0.3}] \quad \text{(Eq.6)}$$

In this equation, $K_{cend(R)}$ is the value recommended by FAO56 in the late growth period of flax (0.40); RH_{min} is the average daily minimum relative humidity of flax in the late growth period (20–80%); and h is the average plant height in the late growth period, (0.1-10 m). After modification, the K_{cend} of flax was 0.42.

WR of Flax Calculated Using the K_c Method

Using *Equation 2*, the ET_0 from *Fig. 7*, and the modified K_c values, the K_c of flax in initial, fast, middle, and late growth stages were found to be 0.21, 0.58, 0.85, 0.42, and the average K_c of flax throughout growth was 0.59 (*Fig. 9*). Using the ET_0 values at the different growth stages in flax, the WR of this crop in the agro-pastoral ecotone of middle region of Inner Mongolia was found to be 16.24 mm, 102.42 mm, 132.38 mm and 62.40 mm, in the initial, fast, middle and late growth stages, respectively. The overall WR of flax with subsurface drip irrigation is therefore 313.44 mm.

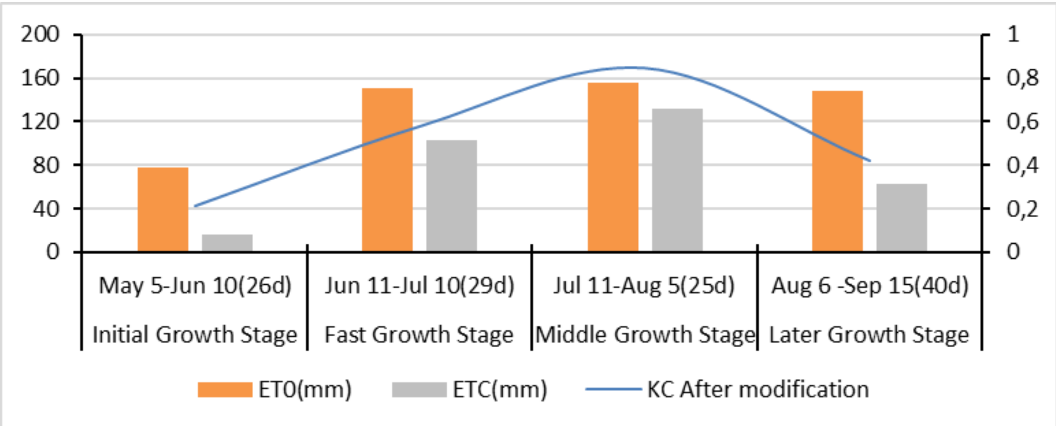

Figure 9. *Modified crop coefficient (K_c) and calculated water requirements of flax*

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Discussion

Irrigation increased the dry matter accumulation after flowering, and also increased the dry matter contribution to oilseed flax seeds (Cui et al., 2015b). The average yield of flax under irrigation was higher than that without irrigation, but some studies had shown that excessive irrigation will not significantly affect the yield of oilseed flax grain, and excessive irrigation will significantly reduce the photosynthetic products and yield of flax (Bauer et al., 2015). Therefore, proper irrigation amount and time were two important components of improving flax yield and effectively using soil water, and the Kc values in the early and middle to late stages of growth are generally considered to be 0.35 and 1.15. In the agro-pastoral ecotone of middle region of Inner Mongolia, soil water consumption is mainly interspecific evaporation when flax is in seedling stage. The K_c value in this stage is relatively small, usually less than 0.4, and the K_{cini} using insufficient irrigation test was estimated to be 0.21, decreased by 40%. Growth speed is accelerated at higher temperatures; vegetative growth and reproductive growth are positively correlated in the fir–budding stage. After flax enters the rapid growth and development stage, the K_c value increases to the maximum K_{cmid}, 0.85, decreased by 26%, in the budding–flowering stage. At the late growth stage in flax, the cultivation and irrigation stop, and the leaves gradually turn from green to yellow, and nutrients begin to transfer to the seeds. After this stage, K_c starts to decline gradually, until it reaches a lower K_{cend} of 0.42.

Compared with field measurement of WR in flax, the K_c method recommended by FAO 56 was used. After modification, the calculated WR of crops is often smaller, especially in the initial growth stage with subsurface drip irrigation. Irrigation and application of N can significantly improve the effective grain size and grain yield of oilseed flax and *Kc* during the entire growth stage was about 0.85, which indicated that the coupling of water and fertilizer was an efficient management mode for flax in arid and semi-arid areas (Cui et al., 2019, 2020). Drip irrigation is also often used for crops in the agro-pastoral ecotone in North China, such as monocropping and rotation of winter wheat and summer corn. The calculated crop water requirement was found to be lower by using the FAO recommended method (Liu et al., 2010). In order to more accurately describe the crop coefficient at the initial stage of crop growth, some studies had also adopted the Dual crop coefficient method, which subdivides the crop coefficient into basic crop coefficient and soil evaporation coefficient (Zhao et al., 2013; Tan et al., 2022). However, the phenomenon that the calculated crop water requirement at the initial stage of crop growth was smaller has also emerged.

K_c comprehensively accounts for the effects of crop characteristics and soil evaporation. At the beginning of growth, flax plants are short, and leaf coverage is small. At this time, K_c is affected by irrigation cycle and moisture ratio in drip irrigation. The research on oilseed flax showed that the amount of irrigation and nitrogen fertilizer application had a significant impact on dry matter accumulation and distribution (Cui et al., 2016). Water and nitrogen coupling significantly affected nitrogen accumulation in flax after budding. The FAO 56-recommended method mainly considers the irrigation form with a long period, while the drip irrigation cycle is short and the low irrigation each time. The planned wet layer was not considered in the K_c method, while the planned wet layer of drip irrigation is far less than that of surface irrigation and sprinkler irrigation, so the calculated WR of crops is relatively small. In the middle stage of growth, because the fields were all covered with flax leaves, the water consumption of farmland was mainly plant transpiration, and the influence of soil texture and irrigation methods on K_c was

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gradually reduced, and the calculated crop WR at this stage and later were close to the measured values.

K_c is related to, and accounts for, the average impact of soil moisture, considering the combined effects of plant transpiration and soil evaporation; this method is more appropriate for surface irrigation and sprinkler irrigation with intervals of ten days or more than ten days, and the calculated ET_c values generally more accurate. When applying K_c in a drip irrigation system, given the short irrigation period and obvious local irrigation, the K_c value calculation in middle and later growth periods still deviates to some extent from the observed K_c, even when K_c is adjusted for the average impact of soil moisture. Combined with meteorological data and crop growth characteristics, the single crop coefficient method could be used to calculate the water requirement for drip irrigation of flax in the agro-pastoral ecotone of middle Inner Mongolia. Even if the calculation error is within the allowable range, it is also necessary to consider the impact of different irrigation forms and the coupling effect of water and fertilizer.

Conclusions

The water requirement of flax under full irrigation was estimated to be 327.4 mm (61.08, 98.67, 104.87 and 62.78 mm, respectively, in the emergence–fir, fir–budding, budding–flowering, and filling–maturing stages. The daily average WR was greatest during the budding–flowering period, at 4.19 mm/day (in which ET_0 was also greatest). The WR in this stage was 32.03%; this stage therefore represents a key period for WR in flax.

According to FAO 56, there are four stages of growth (initial, rapid, middle, and late growth stage). After modifying the K_c as recommended by FAO 56, the K_c values of the four stages were 0.21, 0.58, 0.85 and 0.44. Over the whole growth period, the K_c of flax was 0.59.

In the agro-pastoral ecotone of middle Inner Mongolia, the irrigation quota of underground drip irrigation in flax was 210 mm, that is, the water supply was sufficient during crop growth stage. The crop WR, calculated using a modified K_c, was 313.44 mm. This is 10% lower than the observed value of approximately 327.4 mm.

In this article, the K_c of flax recommended by FAO56 was modified to obtain K_c of the different growth stages of flax under drip irrigation in the argo-pastoral ecotone of central Inner Mongolia, to provide quantitative theoretical support for better application of crop coefficient method of the Food and Agriculture Organization of the United Nations, and water consumption management and crop structure adjustment in the region.

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