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PHAM VAN BAN

RESEARCH ON REASONABLE IRRIGATION REGIME FOR BLACK PEPPER PLANTS IN THE CENTRAL HIGHLANDS

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Science Facilitator: Assoc. Prof., Dr. Doan Doan Tuan
Assoc. Prof., Dr. Nguyen The Quang

Reviewer 1: Prof., Dr. Tran Viet On
Reviewer 2: Assoc. Prof., Dr. Nguyen Trong Ha
Reviewer 3: Dr. Ha Minh Thanh

The thesis will be defended in front of the Dissertation Judging Committee at the Academy level.
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INTRODUCTION

1. Necessity of the dissertation topic

Vietnam is one of the seven countries with the world's greatest black pepper growing area, and it was the world's leading producer and exporter of black pepper in 2018, accounting for over 40% of output and more than 60% of market, with exports to over 105 countries and territories.

Black pepper is cultivated mostly in the Central Highlands and Southeast provinces, which account for 93.53 percent of the country's area, and has an annual export value of about 1 billion USD.

Numerous localities in the Central Highlands have experienced severe droughts in recent years as a result of climate change and El Nino due to the continuous drought, larger and larger areas of cropland in the Central Highlands have been lost. The total impacted area in three years from 2014 to 2016 was 350,000 ha, nearly 15 times more than the drought in 1997-1998 and about 10 times higher than the drought in 2002-2003. As a result, to combat drought and maintain production, several functional sectors and agencies have proposed numerous solutions to this problem, but none of them have met the requirements.

Drought has reduced pepper productivity in the Central Highlands, from 26.1 quintals/ha in 2015 to 24.4 quintals/ha in 2016 and 23.8 quintals/ha in 2017. Irrigation and drainage are incompatible with the growth process of black pepper plants, resulting in decreased disease resistance and low productivity. For example, it is necessary to stop watering black pepper plants during the stages of flower bud differentiation and flowering during the flowering stage, the plants require high humidity for easy pollination. Proper soil and air moisture conditions will aid the plant in completely differentiating flower buds, flowering uniformly and at the appropriate time, which is necessary for great productivity and quality.

In the Central Highlands provinces, the black pepper plant is a key plant with high economic value, contributing to hunger eradication and poverty reduction. Most cereals, food crops, industrial crops, and fruit trees have had their irrigation regimes and techniques thoroughly researched, with standards and regulations promulgated for growers. On the other hand, the water demand, a reasonable irrigation regime, and irrigation techniques for pepper plants have not yet been thoroughly researched. Irrigation for pepper plants is primarily based on local knowledge and the application of small-scale research findings, which are among factors contributing to the pepper plants' unsustainable growth.

The dissertation's topic is important and has both scientific and practical value, as it contributes to the long-term growth of black pepper and agricultural production in our country.

2. Dissertation purposes

- Determine a reasonable irrigation regime for black pepper plants in the business stage in the Central Highlands.
- Propose the crop coefficient Kc to serve the design calculation and irrigation plan for black pepper plants in the Central Highlands.

3. Scientific and practical significance of the dissertation

3.1. Scientific significance

Quantification of water need, a reasonable irrigation regime in accordance with the water physiology of black pepper plants in the business stage, and weather conditions in order to meet the water demand for flower bud differentiation, flowering and fruiting, fruit maturation and harvesting, ensure the growth and development process well, laying the groundwork for high and stable productivity in production and subsequent crops in the Central Highlands.

3.2. Practical significance

In the research area and the Central Highlands, a reasonable irrigation regime is applied to ensure high and stable crop yields for pepper plants in the business stage. Appropriate irrigation formula contributes to the efficient use of water resources of the research area and Central Highlands.

4. New contributions of the dissertation

1. The dissertation has quantified the basic criteria for defining a proper irrigation regime for black pepper plants in the business stage. Suitable soil moisture for pepper plants in the business stage in the Central Highlands:

+ Flower bud differentiation stage: β_{tn}= (65-75)% β_{dr}

+ Flowering, fruiting and harvesting stage: β_{tn}=(80-100)% β_{dr}.

2. The proposed crop coefficient Kc for black pepper plants in the business stage in the Central Highlands, divided into three growth stages:

+ Stage of flower bud differentiation Kc=0.8-1.02

+ Stage of flowering, fruiting and fruit maturation Kc=1.11-1.12.

+ Stage of fruit maturation and harvesting Kc=0.83-0.93.

5. Organization of the dissertation

The dissertation is 136 pages long, with 41 pages of appendices of calculation results, 37 tables, 49 figures and 4 scientific works by the author that are related to the published thesis.

The content of the dissertation includes an introduction, 3 chapters, conclusion and recommendations.

Chapter 1- Overview of irrigation regime studies

Chapter 2- Scientific basis and research methods

Chapter 3 - Research results and discussion.

CHAPTER 1. OVERVIEW OF IRRIGATION METHOD STUDIES

1.1 Overview of research results on irrigation regimes

1.1.1. Evapotranspiration (ETc) and crop coefficient Kc

The evapotranspiration (ETc) of some perennial crops and fruit trees, such as avocado, cocoa, coffee, grapefruit, and orange, ranges from 650 to 1,200mm/year on average.

Crop coefficient Kc of industrial plants and fruit trees such as: apple, peach, pear, orange, tangerine, etc. can be divided into 3 stages: the first stage Kc_{ini} is from 0.3-0.7, the middle stage Kc_{mid} is from 0.65-1.2 and the last stage Kc_{end} is from 0.45-0.9. Coffee tree in the business stage has the Kc_{ini} from 0.9-0.1.05, Kc_{mid} from 0.95-1.1 and Kc_{end} from 0.95-1.1.

1.1.2. Suitable soil moisture for plants

For some industrial trees and fruit trees such as grape, dragon fruit, etc., soil moisture from (70-100)%βdr is suitable for plant growth and has higher yields than other humidity ranges.

1.1.3. Reasonable irrigation method for fruit trees and industrial trees

Under certain conditions, a reasonable irrigation regime can provide water for plants, allowing them to achieve a stable and striving yield.

Dragon fruit tree in the business stage: irrigation rate from 71.5 ÷ 82.1 m^3/ha; from month (1÷2): 6-7 days/time; month (3÷4): 4-5 days/time, month (5÷10): 25-30 days/time; month (11÷12): 8-10 days/time. The total irrigation rate for the whole crop ranges from 1937.5 m^3/ha to 2662 m^3/ha. Tea tree (Phu Tho) has the total irrigation rate of 2,924m^3/ha/year, irrigation rate 200m^3/ha/time and the number of irrigation times 14 times/year. Grapefruit tree (Hanoi) is watered the first time between harvesting and flowering, the second time between flowering and fruiting and the third (and fourth) times between fruiting and harvesting. The irrigation level of the first two stages is 176m^3/ha and of the last stage is 132m^3/ha.

1.1.4. Water retention stage of fruit trees and industrial trees

Some terrestrial crops need a period of water retention (to create drought-like conditions) to flower and produce high-yielding fruit. This period may occurs before flowering or fruiting. Coffee trees need retain water for 1.5 to 2 months after harvesting to differentiate flower buds and flower simultaneously. Some citrus fruit trees such as orange, grapefruit, tangerine, etc. need about 2-4 weeks to retain water before growing sprouts and flower buds. Concentrated flowering is a premise for high yield.

In Australia, regulated deficit irrigation (RDI) for fruit trees increases water efficiency by approximately 60% without loss of yield while increasing fruit set and fruit quality. It is applied during the stage of slow fruit growth. Peach trees need to retain water in the stage of slow fruit growth (from October to January next year). Pear trees in the business stage require water retention throughout the slow fruit growth stage, which lasts around two months. The grape trees for wine production need to retain water shortly after the fruiting and fruit maturation.

1.2. Overview of research results on irrigation regime for black pepper plants

In India, in the dry season, trees need watering 7 liters/day or 100 liters/week, with an interval of 8-10 days/time. In the summer, watering is required every two weeks with an irrigation rate of 50 liters for each 15-and-over-year-old black pepper pillar, 40 liters for each 11-15-year-old black pepper pillar and 30 liters for each 5-10-year-old black pepper pillar, which can increase the yield by 90 to 100%. In Indonesia, where there is no rain for three days after planting and the temperature is extremely hot, watering pepper plants at the early stage at a rate of 0.5 liters/pillar/time is recommended.

Several research conducted in Vietnam reveal the following findings: irrigate by sprinkler under the canopy and at the root, 35 - 40 liters/pillar/time; traditional tank irrigation (watering directly at the root), 100-120 liters/pillar/time; drip irrigation, 28-32 liters/pillar/time, 3 days/time. Flowering bud differentiation stage (30 to 45 days): stop watering, no irrigation, if the drought persists, irrigate once every 3-7 days on average with 20 to 30 liters/pillar/time.

The published works have specified the amount and cycle of irrigation, but the amount of watering required to meet the plant's growth and physiological needs, particularly during the flowering bud differentiation stage, has not been determined, and the scientific basis for proposing a reasonable irrigation regime for the plant has not been established.

CHAPTER 2:SCIENTIFIC BASIS AND RESEARCH METHODS

2.1. The scope of the research

The research covers the Central Highlands, with Gia Lai province serving as a case study. The black pepper plant at the business stage has the physiological stages for watering as follows:

- Flowering bud differentiation stage
- Flourishing, fruiting, nurturing, and ripening fruit until harvest.

The research took place over a 3-year period, from 2016 to 2019.

2.2. Location of experimental research

The experimental research was conducted in the commune of IaBlang, Chu Se District, Gia Lai Province.

2.3. The scientific basis for determining a reasonable irrigation regime for black pepper plants in the Central Highlands

2.3.1.Based on the water requirements of the plant during its growth stages

a. Flowering bud differentiation stage

The black pepper plant has a very special characteristic that is each collar, bough, and branch contains a bud that can later develop into a flower if it is awakened and completely differentiated flower buds. Within 15 days of suitable drought conditions, abscisic acid levels increase while cytokinin and gibberellic acid levels decrease, which is a favorable condition for flower bud differentiation and flower development. This is when the plant transforms from focusing on vegetative organs to focusing on reproductive organs (flowering and fruiting). When the plant has flowered, it is considered complete; the tree's flowering was initiated approximately 20 days ago by ceasing to water the plant. During this time, it is necessary to stop watering or irrigating a small amount of water. Watering should be stopped for a period of 30 to 45 days. A healthy black pepper plant that cannot differentiate flower buds will fail to transform, may flower twice, or have only leaves and then produce a few flowers, which greatly affects the productivity in the future. For black pepper plants, the first 30–45 days after ceasing watering are important in determining the crop's overall productivity.

b. Flowering and fruiting stage

When the plant begins to bloom, high air humidity plays an important role in pollen collection. If the humidity level is low during the blooming period of the pepper plants, it is necessary to irrigate actively. At this stage, water consumption is high because the favorable conditions for flowering, pollination, and fruiting are created by the high soil moisture.

c. Fruit development stage

During the period of fruit formation and shell and seed development, in order for the plants to grow well and have high productivity, regular watering is required to keep the soil moist, the plants easily absorb water, and the fruits develop well.

d. Ripening and harvesting stage:

The black pepper plants' water and nutrient requirements begin to decrease. Stop watering for approximately 10-15 days at the end of the stage.

2.3.2. Based on plant protection conditions.

Rapid death disease and slow death disease are both threats to black pepper plant growth and development.

Rapid death disease is caused by a pathogenic fungus that grows in the soil and is active during the rainy season and in the garden's high air humidity conditions. When black pepper plants are infected with rapid death disease, it will die completely within about 1-2 weeks.

Slow death disease is also known as yellow leaf disease, nematode disease, etc. Due to a harmful combination of nematodes and fungi in the soil, diseased black pepper plants grow slowly, its leaves turn yellow and wilt gradually, and their productivity is low. After 1-3 years, diseased plants die. In dry months, the disease rate and yellow leaf disease index are higher, with a peak in February. The lowest statistics are in the middle of the rainy season (August). A well-managed irrigation regime will help prevent the spread of those diseases. It is necessary to have an adequate supply of water during the dry season. Irrigate sparingly to prevent disease from spreading to neighboring plants. When watering, do not let the moisture exceed the humidity of the garden.

2.3.3.Based on the pedology characteristics and the nature of water in the soil.

The effective amount of moisture is the amount of water in the soil that falls within the range of moisture from the garden moisture holding capacity to the withered plant moisture corresponding to the water holding capacity of soil (from 0.33 to 15.2 bar).

When soil moisture levels fall below a certain value in the water-effective range, which is the lower limit of moisture for high-productivity plants, productivity declines dramatically. The amount of water contained in the area above the lower limit of moisture is the suitable amount of water for the plant. According to FAO document No. 56 [66], the readily available water is determined by the following formula (2.1):

$$RAW = p.TAW \qquad (2.1)$$

Where:RAW– The readily available soil water in the root zone [mm] p- Average fraction between the readily available soil water and the total available water (TAW) before moisture stress (reduction in ET) occurs [0-1].

The formula for determining the lower limit of acceptable humidity is as follows (2-3):

$$\beta_{min} = \beta_{dr} - p.(\beta_{dr} - \beta_{ch}) \qquad (2.3)$$

β_{min}:The lower limit of acceptable humidity during watering (% TLDK).

β_{dr} : Soil moisture capacity (% TLDK).

β_{ch} : Wilting point (% TLDK).

p: Average fraction between the readily available water (RAW) and the total available water (TAW), $(0 \leq p \leq 1)$.

Values for p are listed in table 22 in FAO document No. 56 [66] and table 39 in FAO document No. 24 [65]. The factor p differs from one crop to another. The factor p normally varies from 0.30 for shallow rooted plants at high rates of ETc (> 8 mm/day) to 0.80 for deep rooted plants at low rates of ETc (< 3 mm/day). A value of 0.50 for p is commonly used for many crops.

2.4. Research Subjects

- Determining the basic criteria in research on plant watering (soil physical and chemical properties, plant characteristics and water physiological characteristics of black pepper plants).
- Experiment with different irrigation formulas

+ Determine the irrigation formula in the study area.
+ Determine the soil moisture changes of the irrigation formulas
+ Determining the growth and development of black pepper plants

- Determine the irrigation method for the corresponding irrigation formula
- Determine the coefficient Kc of pepper plants over the course of a business period

2.5. Research Methods

- Derived method.

- Experimental method to experiment with irrigation formulas based on water physiological characteristics of black pepper plants over the course of a business period; measure and collect data on black pepper irrigation methods and yield.
- Statistical analysis method (regression correlation) to process data, analyze and evaluate research findings.

2.5.1. Determination of soil physical and chemical properties

A soil pit is excavated to observe the soil profile and collect soil samples for analysis to determine the physical and chemical indicators of the experimental area's soil. The results are as follow:

The experimental area's soil is red-brown soil on Basalt (Ferralsols) of cultivation layer from 0÷47cm, wet density $d=1.10g/cm^3$, dry density D=2.5g/cm3, porosity A=56.46%. The soil mechanical composition contains 17.2% sand, 60.55% clay and 22.25% limon. Maximum soil moisture is β_{dr}= 40.87% TLDK, and wilting point is β_{ch}= 49.29%β_{dr}. The infiltration rate reaches a stable level at about 0.15cm/min after 8 hours, equivalent to 90mm/hour, which is the medium-fast rate. During the dry season, the groundwater level is approximately 15m above the ground. This soil type is suitable for a variety of industrial crops such as coffee and black pepper, but due to its strong horizontal and vertical infiltration, irrigation measures must be carefully monitored to avoid water waste.

2.5.2. Determination of pepper plant roots and depth of irrigation layer

The three-year-old black pepper tree is of the Vinh Linh cultivar. Beside a wooden pillar, it stands at 3.5m in height and 0.65m in radius, with roots concentrated at a depth of 0-50cm and a radius of 60-70cm. This part contains 97% of the weight and 92% of the root volume, and the roots tend to grow horizontally. Climbing roots grow from the aerial trunks and help the tree grow by clinging to the pillar. Based on the root structure, choose the depth of the irrigation layer H=0.5m and the radius of irrigation R=0.65m.

2.5.3. Determination of irrigation formulas and setting up field experiments

2.5.3.1. Determination of experimental formulas in the field

To determine β_{min} for irrigation formulas, we use scientific basis and the coefficient p, which is the average fraction between the readily available soil water (RAW) and the total available soil water (TAW) before moisture stress (reduction in ET) occurs. The experimental formula is as follows:

Table 2.13. Experimental and control irrigation formulas

Irrigation formula	*Flower bud differentiation stage*	*Main – Flowering – Riping stage*
F1	(60-70)%β_{dr}	(80-100)%β_{dr}
F2	(60-70)%β_{dr}	(75-100)%β_{dr}
F3	(65-75)%β_{dr}	(80-100)%β_{dr}
F4	(65-75)%β_{dr}	(75-100)%β_{dr}
F5	(65-75)%β_{dr}	(85-100)β_{dr}
C	Control formula	Control formula

Experimental setup based on the following principles: triangle, each irrigation formula 3 times, drip irrigation technique.

2.5.4. Determination of the reasonable irrigation regime

According to the irrigation formulas of previous years, the results of field experiments determined the level of irrigation, the number of irrigation times, the interval of irrigation, the total amount of irrigation, the width of the canopy, the height of the tree and the crop yield. After three years, the yield value and annual irrigation level must be determined. In accordance with the management and operation conditions of the people, the reasonable irrigation regime results in low total irrigation rate yet the highest, most cost-effective crop yield and irrigation water productivity.

2.5.5. Determination of the coefficient Kc of pepper plants in the business stage

$$Kc = \frac{ETc}{ETo} \qquad (2.19)$$

Where: + ETc is the crop evapotranspiration (mm)

+ ETo is the reference evapotranspiration (mm)

+ Kc is the crop coefficient.

Crop coefficient Kc is determined on the basis of theory and experiment. ETc is determined using a reasonable irrigation regime in the field, whereas ETo is determined using climatic criteria in the Central Highlands, as calculated using the FAO's CROPWAT software. Utilize IBM SPSS software to determine the reliability of the coefficient Kc.

CHAPTER 3: RESEARCH RESULTS AND DISCUSSION

3.1. Results of experimental research are used to define the reasonable irrigation regime.

3.1.1. Irrigation regime for black pepper plants based on experimental results

3.1.1.1. Flowering bud differentiation stage

The number of days retained by the three experimental crops ranged from 39 to 44 days, with the maximum retention occurring with the formula CT3 of the third crop (44 days), and the average of the three crops with the formulas CT1, CT2, CT4, and equal control formula being 41 days.

Soil moisture of irrigation formulas is (60-70)%β_{dr} and (65-75)%β_{dr}. The irrigation level in crop 1 (2016-2017) ranges from 300-324m^3/ha, crop 2 (2017-2018) ranges from 60-150m^3/ha, and crop 3 (2018-2019) ranges from 136-240m^3/ha. In terms of the average irrigation level of three crops compared to the control formula, the CT1 to CT5 formula reached 73%, 70.7%, 74.3%, 71.4%, and 71.4%, respectively, of the control formula irrigation level. CT2 has the lowest average irrigation rate of any of the three smallest crops

(198m^3/ha/crop). Watering is provided infrequently, 4 times for crop 1 (2016-2017), and 1 to 2 times for crop 2 (2017-2018). The typical watering interval is 5-6 days/time, and the average watering rate is 30 liters/head/time.

3.1.1.2. Flowering, fruiting and harvesting stage

Irrigation formulas' soil moisture limit is (75-100)%β_{dr}, (80-100)%β_{dr} and (85-100)%$_{dr}$. The irrigation level in this phase accounts for a large proportion of the year while the irrigation level in the third year is the highest; and the watering levels of the experimental irrigation formulas are lower than the control ones; The irrigation formulas CT1, CT3 rise from the first to the third crop, whereas the formulas CT2, CT4, CT5 are the smallest in crop 2 and the greatest in crop 3; the irrigation formulas have an irrigation level of 1,362-1,508m^3/ha in crop 1 (2016-2017), 1,322-1,456^{m}3/ha in crop 2 (2017-2018), 1,842-1944m^3/ha in crop 3 and an irrigation frequency of 12-18 times, 9-16 times, 13-22 times respectively; the control irrigation level ranges from 2400-2640m^3/ha, number of irrigations 16-17 times. The number of irrigation times are different in experimental formulas while CT5 has the largest number of watering times from 18-22 times, notably in the third crop, up to 22 times/crop, which are greater than the control formula, CT1, CT2, CT3 and CT4 are fewer than the control formula. The third crop has the highest number of irrigations of all the formulas. The average number of irrigations for 3 crops with CT2, CT4 is the lowest. The interval between watering times is 10-12 days/time, while the watering rate is 50-60 liters/head/time.

3.1.1.3. Full-season irrigation regime

Each year, there are eight months to irrigate three experimental crops, with the majority of the watering concentrated in the months of December, January, and February.

The irrigation level of the whole crop was from 1556 to 2026m^3/ha with CT1, from 1382 to 2154m^3/ha with CT2, from 1672 to 2022m^3/ha with CT3, from 1388 to 2184 m^3/ha with CT4, from 1606 to 2030m^3/ha with CT5, from 2660 to 2900m^3/ha with control formula in 3 experimental crops. The average total irrigation water applied to the three experimental crops is less than that applied to the control formula;

The number of watering times for 3 crops is as follows: CT1 from 14÷18 times, CT2 from 10÷15 times, CT3 from 15÷19 times, CT4 from 10÷16 times, CT5 from 18÷25 times, the control formula from 19÷20 times; The number of times of watering all 3 crops with CT5 formula is the most, equal to 120-180% compared with other irrigation formulas; however, the average of 3 cultivation crops of the formulas is different, increasing from CT3,CT4,CT1, CT2÷ CT5.

3.1.2. Height, leaf width, and black pepper yield

3.1.2.1. Black pepper plants (pillar) height

Through three experimental harvests, black peppers with formula CT4, CT5, and CT2 increased by 0.45-0.33m, 0.62-0.72m, and control formula increased by 0.42m, respectively. Thus, the experimental plants all increased in height and increased more than the control plants.

3.1.2.2. Black pepper tree foliage width (pillar)

The width of the black pepper tree canopy expands steadily from crop 1 to crop 3, with the formulas CT1, CT2, and CT3 increasing more than the control treatment (15cm, 16cm, and 17cm, respectively, compared to 8cm), demonstrating that with proper watering, the tree increases in height and canopy width.

3.1.2.3. Black pepper productivity

Black pepper yields in three experimental crops of CT1 CT2, CT3, CT4, CT5, and the control formula ranged between 4.88-5.03 tons/ha, 4.93-5.02 tons/ha,4.99-5.12 tons/ha, 4.94-5.09 tons/ha, 4.84 -4.99 tons/ha, and 4.90-4.74 tons/ha, respectively.

The black pepper yields 4.5 tons/ha or more in the experimental area, and the formula CT3 increases from crop 1 to crop 3 and also the highest among the experimental formulas, at 5,126 tons/ha. The yield of formula CT1, CT2, CT4, and CT5 fluctuates irregularly, with the second crop being lower than the first, but the third crop being higher than the first and second crops.

The yield difference of the formulas is from 1-2 quintals/ha. Compared with the control formula, the average yield of 3 crops of CT3 formula increases the highest at 182.7kg/ha, followed by CT4, CT1, CT2, and CT5 at 75.3kg/ha, 20kg/ha, 17.3kg/ha and 10.3kg/ha .

3.1.3. Relationship between irrigation water volume and yield

The average amount of water for irrigation of crops from formula CT1 to CT5 is not significantly different, ranging from 1,755m^3/ha, 1,791m^3/ha, 1,793m^3/ha to 1,819m^3/ha, but the difference in crop yield is 4,878 kg, 4,885 kg, 4,888kg, 4,943kg and 5,051kg, respectively; compared with the control formula, the amount of irrigation water in the formula was 58.7 ÷ 64.8%, but the yield increased from 10.3kg ÷ 182.7kg/ha, the experimental irrigation formulas saves water and gives higher yields than the control formula, the formula CT3 gives the highest yield. Figure (3.12) below illustrates the relationship between yield and irrigation water volume in three crops:

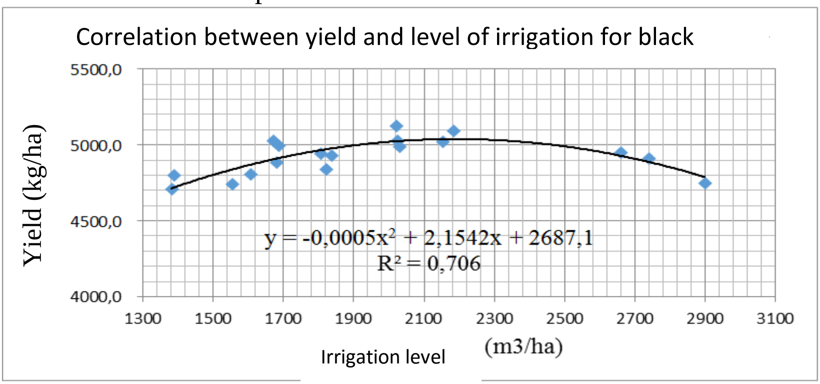

Figure 3.12. The relationship between yield and irrigation level of black pepper crop

The figure (3.12) shows that, if black pepper plants are watered at a low level of 1,382m^3/ha/crop will yield 4,712 kg/ha/crop. When the irrigation rate is gradually increased, the yield also increases. When the irrigation level increases to 2184m^3/ha/crop, the yield increases to 5090kg/ha/crop, however, if irrigation is increased further, the yield tends to drop, watering at a high level of 2,900m3/ha/crop yields only 4,746 kg/ha/crop; Thus, as illustrated in figure (3.12), increasing the irrigation level increases the yield, but if the irrigation level is increased continuously, the yield decreases to a certain value.

3.1.4. Irrigation water productivity

IWP irrigation water productivity (kg/m^3) is calculated as the ratio between agricultural product volume, CY (kg/ha), and irrigation water volume, AW (m^3/ha):

$$\text{IWP} = \frac{CY}{AW} \text{ (kg/m}^3\text{)} \qquad (3.2)$$

Calculation results in the three research crops are shown in the figure chart (3.13) below:

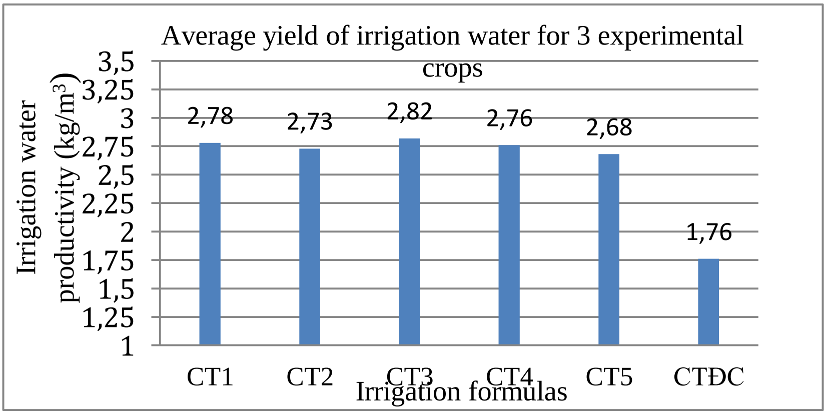

Figure 3.13. Average yield of irrigation water for three experimental crops

The average irrigation water yield of black pepper plants in the three experimental crops varied between the irrigation formulas, the formula CT3 achieved the highest at 2.82 kg/m^3, formula CT5 reached the lowest 2.68 kg/m^3. However, the experimental irrigation formulas were higher than the control ones, at 2.78 kg/m^3, 2.73kg/m^3, 2.82 kg/m^3, 2.76 kg/m^3, 2.68kg/m^3, respectively, compared to 1.76 kg/m^3. Thus, watering pepper plants according to the experimental formulas was more effective than watering with the control formula, and the formula CT3 produced the highest average yield of irrigation water.

3.1.5. Economic efficiency of black pepper production in three experimental crops

Economic efficiency of black pepper production is calculated on the basis of crop yield, product selling price, and intermediate costs such as: Fertilizers, pesticides, electricity, labor, depreciation of investment assets. Economic efficiency is described in table (3.10):

Table 3.10. Economic efficiency of black pepper production in three experimental crops

No	Content	CT1	CT2	CT3	CT4	CT5	Control formula
1	Productivity NS (ton/ha)	4.88	4.88	5.05	4.94	4.87	4.86
2	Selling price C (1000VND/kg)	41.3	41.3	41.3	41.3	41.3	41.3
3	Intermediate cost (10^6VND/ha)	64.3	64.3	64.3	64.3	64.3	68.5
4	Mixed income (10^6VND/ha)	137	137	144	139	137	132
5	Capital efficiency (times)	2.14	2.14	2.24	2.17	2.13	1.94

The formula CT3 has higher economic efficiency, with a mixed income of 144 million VND/ha and a capital efficiency of 2.24 times.

3.1.6. Determining a reasonable irrigation formula for black pepper plants

After three years of experimental research, pepper plants increased in height and width of canopy compared to the original, with black pepper plants with formula CT3 exhibiting the greatest increase. The yield in each experimental formula increased with the age of the plants from 4 to 6 years old, the yield difference between crops was between 1-2 quintals/ha. In the 3 studied crops, the black pepper yield was 4.5 tons/ha or more, the third crop of all the formulas reached over 5 tons/ha, the average of the three highest crops was the formula CT3 reaching 5,051 tons/ha; Compared with the control formula, the yield of formula CT3 increased the most (over 182.7kg/ha), followed by formula CT4, CT2, CT1, CT5 increased 75.3 kg/ha, 20 kg/ha, 17.3kg/ha, and 10.3kg/ha, respectively, while maintaining a watering level of about comparable to 63-64% of the control formula. Irrigation water productivity and economic efficiency were higher than that of the control formula, with the formula CT3 showing the greatest increase. Thus, the CT3 irrigation formula maximizes plant height, foliage width, crop yield, irrigation yield, and economic efficiency. It is an irrigation formula that is beneficial to plant growth; it is a reasonable irrigation formula that includes the following parameters: The soil moisture is suitable for the flower bud differentiation stage (65-75%β_{dr}), flowering, fruiting and harvesting (80-100%β_{dr}), yield ranging from 4.996 tons/ha to 5.126 tons/ha, and the average total irrigation level is 1,790m^3/ha/year.

3.2. Calculation of the crop coefficient Kc

3.2.1. ETo calculation results in 3 experimental crops

ETo value calculated from climatic factors collected at PleiKu-Gia Lai station and the Penman-Monteith formula and CROPWAT software, the calculation results are shown in table (3.11) below:

February, March and April have the highest potential evapotranspiration, while July, August, and September have the lowest.

The development of ETo in the experimental crops was relatively similar, with only a small difference between the years: crop 1 (2016-2017) was 1,482mm, crop 2 (2017-2018) was 1,472mm and crop 3 (2018-2019) was 1.484mm.

Table 3.11. Calculated ETo in 3 experimental crops

Growth stage of pepper plants	*Month*	*crop 1 ETo (2016-2017) mm/month*	*crop 2 ETo (2017-2018) mm/month*	*crop 3 ETo (2018-2019) mm/month*
Harvesting stage	III	168.95	155.00	149.11
Flowering bud differentiation stage	IV	154.80	149.70	162.00
Flowering and fruit setting stage	V	152.21	130.20	146.32
	VI	122.10	115.50	100.50
	VII	124.93	94.240	89.90
Green fruit stage	VIII	98.89	112.22	85.87
	IX	99.30	112.50	110.40
	X	105.09	109.74	130.82
Fruit ripening stage	XI	111.00	104.10	117.60
	XII	97.65	112.84	120.59
	I	123.07	131.13	126.17
	II	124.60	145.04	145.04
	Total	***1,482.59***	***1,472.21***	***1,484.32***

Development of ETo by month in 3 experimental crops (Figure 3.21):

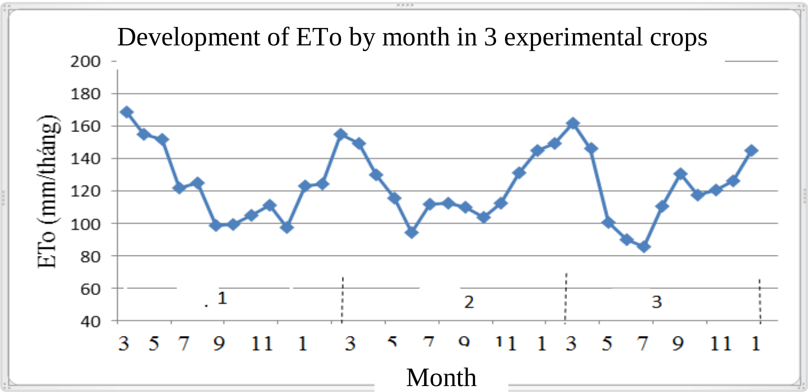

Figure 3.21. Developement of ETo by month in 3 experiments

3.2.2. Amount of water required- ETc

The amount of water required by month is shown in the table (3.12) as follows:

Table 3.12. Summary of ETc by month in 3 experimental crops

Growth stage of pepper plants	*Month*	*crop 1 ETc (2016-2017) mm/month*	*crop 2 ETc (2017-2018) mm/month*	*crop 3 ETc (2018-2019) mm/month*
Harvesting stage	III		127.21	117.00
Flowering bud differentiation stage	IV	120.33	134.31	127.64
	V	142.38	142.79	148.46
Flowering and fruit setting stage	VI	136.86	128.40	111.88
	VII	137.75	104.48	100.86
	VIII	114.38	124.00	95.4
Green fruit stage	IX	110.10	127.16	123.08
	X	117.40	125.11	138.52
	XI	123.27	118.95	130.33
	XII	110.40	130.34	130.45
Fruit ripening stage	I	116.85	120.96	116.37
	II	102.71	119.64	121.55
	Total	1,332.43	1,503.35	1,461.54

The results of the 3 experimental crops determined that the reasonable irrigation regime for pepper plants was formula F3, which used the experimental results of 3 crops' field measurements to determine the amount of water required ETc.

The amount of water required varies significantly between years, with crop 2 requiring the most (1,503.35mm/12 months). The dry season months of April and May require the most water because this is when the plants begin to differentiate flower buds, whereas the rainy season months of August and September require the least.

3.2.3. Crop coefficient Kc

The average Kc coefficient of the crops is shown in table (3.15):

Table 3.15. Summary of the average coefficient Kc of the experimental crops

Month	2016	2017	2018	2019	Medium
3		0.82	0.78		0.80
4	0.78	0.90	0.79		0.82
5	0.94	1.10	1.01		1.02
6	1.11	1.11	1.11		1.11
7	1.10	1.11	1.12		1.11
8	1.11	1.11	1.11		1.11
9	1.10	1.13	1.11		1.11
10	1.12	1.14	1.06		1.11
11	1.11	1.14	1.11		1.12
12	1.13	1.16	1.08		1.12
1		0.95	0.92	0.92	0.93
2		0.82	0.82	0.84	0.83

The 3-year average Kc coefficient is shown in Figure (3.22) as follows:

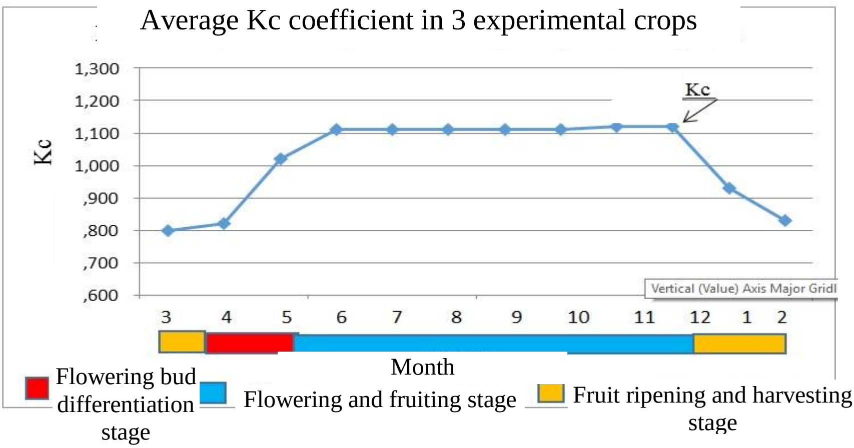

Figure 3.22. Average coefficient Kc in 3 experimental crops

Flowering bud differentiation stage has Kc=0.8-1.02, flowering and fruiting stage has Kc=1.11-1.12, fruit ripening and harvesting stage has Kc=0.93-0.83.

The statistical analysis method and IBM SPSS software are applied to analyze and evaluate the reliability of crop coefficient Kc. The coefficient Kc closely depends on the soil moisture at the beginning and the end of the crop, irrigation level and rainfall. Calculation results Cronbach's Alpha = 0.661> 0.6 is in the reliable range (Nunnally Bernstein, 1994). The test results of the actual measured data all meet the statistical requirements. Crop coefficient Kc ensures reliability.

3.3. Proposed reasonable irrigation regime for black pepper plants in the Central Highlands

3.3.1. Flower bud differentiation stage of black pepper plants

The stage of flower bud differentiation begins at the time of watering and nourishing after harvest, which lasts 41-44 days, at the end of March every year. At that time, stop watering the plants (to create drought-like conditions). Suitable soil moisture is from (65%-75%)β_{dr}, the interval between irrigations is 5-6 days/time and the irrigation rate is 30 liters/pillar/time.

3.3.2. Flowering stage of black pepper plants

Black pepper flowers from May to July, with May and June marking the start of the rainy season. At this stage, the plant requires a lot of water to bloom; the ideal soil moisture level is no less than (80%-100%)β_{dr}, the interval between irrigations is 10-12 days/time, the irrigation rate is 55-60 liters/pillar/time, and the number of watering times is 2-3 times/month. Until July, it rains heavily, so there is no need to irrigate.

3.3.3. Fruiting and green fruit stage of black pepper plants

Pepper fruits from August to October. The plant has a high water demand, requiring soil moisture no less than (80%-100%)β_{dr}. Because this stage is in the rainy season, watering is unnecessary.

3.3.4. Fruit growth stage of black pepper plants

This stage lasts from November to December. The plant has a high water demand due to the dry weather. Watering the plants is required. The soil moisture is no less than (80% - 100%)β_{dr}, the interval between irrigations is 10-12 days/time, the number of irrigations is 2-3 times/month and the irrigation rate is 55-60 liters/pillar/time.

3.3.5. Fruit maturation stage of black pepper plants

It lasts from January to February, which is the driest period of the year; therefore, the plant has a high water demand. Soil moisture is no less than (80%-100%)β_{dr}, the interval between irrigations is 10-12 days/time, the number of irrigations is 2-3 times/month and the irrigation rate is 55-60 liters/pillar/time.

3.3.6. Fruit ripening stage of black pepper plants

Every year at the beginning of March, the fruit is matured, and it does not need to be watered for about 10-15 days to accelerate black pepper ripening. The appropriate soil moisture is no less than (80%-100%)β_{dr}.

3.3.7. Fruit ripening and harvesting stage of black pepper plants

Fruit ripens and is harvested in mid-March. The plant's water demand is high due to high evapotranspiration ETo; therefore, irrigation is required to keep the tree healthy. The soil moisture should be maintained no less than 80%-100% βdr, the interval between irrigations is 10-12 days/time and the irrigation rate is 55-60 liters/pillar/time.

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusion

1.1. In the case of drip irrigation, the effective irrigation depth for black pepper plants in the business stage is 0.5m, and the humidifying radius R=0.65cm.

1.2. In the Central Highlands, soil moisture is suitable for the water physiology of black pepper plants in the business stage:

+ Flowering bud differentiation stage : β_{tn}= (65-75)% β_{dr}

+ The stage of flowering, fruiting and harvesting:β_{tn}=(80-100)% β_{dr}.

1.3. The evapotranspiration rate of black pepper plants ranges from 3.37 to 4.59mm/day, with the highest rates in April, May, and June when the plants are germinating, sprouting, and flowering; and at least once a year in August. The total amount of water required each year ranges from 1,332mm to 1,503mm.

1.4. Reasonable irrigation regime:

+ Total average irrigation rate 1,790m^3/ha/year.

+ Flowering bud differentiation stage: irrigation rate is 30 liters/pillar/time (equivalent to 60m^3/ha), the interval between 2 irrigations is 5-6 days.

+ Stage of flowering, fruiting and harvesting: in May and June irrigate 1-3 times, each time from 55-60 liters/pillar (equivalent to 110m^3/ha to 120m^3/ha/time); No watering in the months of July, August, and September, from October to February of the following year irrigate 7 to 10 times, the irrigation rate is from 110m^3/ha to 120m^3/ha, the interval between 2 irrigations is 10-12 days.

1.5. Crop coefficient Kc determined in 3 stages:

+ Flowering bud differentiation stage: Kc=0.8-1.02.

+ Flowering to matured fruit stage: Kc=1.11-1.12.

+ Fruit ripening and harvesting stage: Kc=0.83-0.93.

1.6. Reasonable irrigation regime to ensure the black pepper productivity in the study area is from 4,996 tons/ha to 5,126 tons/ha.

2. Recommendation

2.1. The research provides an additional reasonable irrigation regime for black pepper plants at the early stage, in order to establish a scientific basis for water supply in accordance with water physiology throughout the plant's life cycle.

2.2. Research results on reasonable irrigation regime and Kc coefficient applied to the design, planning and production of black pepper plants in the Central Highlands give high yield. When there are changes in cultivar, exploratory experiments could be performed in cultivation areas before application.

LIST OF SCIENTIFIC WORKS OF THE AUTHOR RELATED TO THE DISSERTATION HAS BEEN PUBLISHED

1- Bui Cong Kien, Doan Doan Tuan, **Pham Van Ban,** "*Research on the irrigation regime and proposal for a water-saving irrigation technique norm for black pepper in the Central Highlands including drip irrigation and root-zone sprinkler irrigation"*. Journal of Water Resources Science and Technology No. 50, December 2018, pp.101-108.

2- **Pham Van Ban**, Nguyen Vu Viet, "*Scientific basis to determine reasonable irrigation regime for black pepper during commercial stage in the Central Highlands"*. Journal of Water Resources Science and Technology No. 53, April 2019, pp.21-27.

3- **Pham Van Ban**, "*Reasonable irrigation regime for black pepper during commercial stage in the Central Highlands"*. Journal of Water Resources Science and Technology No. 62, October 2020, pp.24-33.

4- **Pham Van Ban**, "*The crop coefficient Kc of black pepper during commercial stage in the Central Highlands"*. Journal of Water Resources Science and Technology No. 62, October 2020, pp.79-87.