Postprint: Study on the Effects of EM Water-Retaining Agent on Flue-Cured Tobacco and Optimization of Its Application Regime

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Abstract

Flue-cured tobacco is an important leaf economic crop in China, which possesses the largest tobacco planting area and total leaf yield globally. Flue-cured tobacco production plays a significant role in enhancing the national economy and fiscal revenue of southwestern provinces (such as Yunnan, Guizhou, and Sichuan). However, periodic drought in tobacco-growing areas frequently affects both the yield and normal maturation of flue-cured tobacco. Therefore, strengthening research on water-saving and drought-resistance technologies for flue-cured tobacco and rationally regulating water supply in tobacco fields are crucial for ensuring high-quality and appropriate yields of tobacco leaves in arid regions. This study prepared EM water-retaining agents using MP3005KM water-retaining agent, straw, EM active calcium, and EM revitalizing solution as primary materials. The effects of different EM water-retaining agent treatments on flue-cured tobacco growth, yield, and quality were investigated, and an entropy weight coefficient evaluation model was introduced to establish an evaluation index system for optimizing the EM water-retaining agent application regime with the best comprehensive benefits. The results showed that: all EM water-retaining agent treatments increased the leaf area per plant of flue-cured tobacco; EM water-retaining agents with straw as the main material (T1 and T2) exhibited more pronounced promotion of leaf area growth during the mid-to-late growth stages; the crop growth model characterizing dynamic changes in leaf area index (LAI) of flue-cured tobacco indicated that treatments T2 (40 g 株 1 EM active calcium + 300 g 株 1 straw) and T6 (40 g 株 1 EM active calcium + 6 g 株 1 MP3005KM) possessed greater potential for LAI increase; EM water-retaining agents significantly increased the net photosynthetic rate (Pn) during the vigorous growth and maturation stages while decreasing the transpiration rate (Tr), thereby regulating photosynthesis in tobacco leaves. Principal component analysis revealed that, compared with the no water-retaining agent treatment, application of EM water-retaining agents significantly improved the "comprehensive quality" of flue-cured tobacco, with EM water-retaining agents using straw as the main material providing the optimal "quality-improving" benefits; the comprehensive principal component values for tobacco quality in T1 and T2 reached 3.25 and 2.76, respectively. Taking into comprehensive consideration factors including "high yield" , "high quality" , "water saving" , and "fertilizer saving" , this study recommends an application regime of 40 g 株 1 EM active calcium combined with 4 500 kg hm 2 straw segments as the EM water-retaining agent. Under this regime, tobacco yield, irrigation water use efficiency, and partial factor productivity of nitrogen fertilizer were 2 433.5 kg hm 2, 0.608 kg m 3, and 27.04 kg kg 1, respectively.

Full Text

Preamble

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Optimization of EM Water-Retention Agent Application in Flue-Cured Tobacco*

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Abstract

Flue-cured tobacco is an important leaf economic crop in China, which has the largest tobacco planting area and total yield worldwide. Tobacco production in southwestern provinces (e.g., Yunnan, Guizhou, Sichuan) plays a crucial role in improving regional economies and fiscal revenues. However, periodic droughts in tobacco-growing regions frequently affect yield and normal maturation. Therefore, strengthening research on water-saving and drought-resistant technologies, and rationally regulating water supply in tobacco fields are key to ensuring high-quality and appropriate-yield production in arid regions. This study used MP3005KM water-retention agent, straw, EM activated calcium, and EM rejuvenation liquid as primary materials to prepare EM water-retention agents. We investigated the effects of different EM water-retention agent treatments on tobacco growth, yield, and quality, and introduced an entropy weight coefficient evaluation model to establish an evaluation index system for optimizing the application regime with maximum comprehensive benefits. Results showed that all EM water-retention agent treatments increased single-plant leaf area, with straw-based treatments (T1 and T2) showing more pronounced promotion of leaf area growth during the middle and late growth stages. The crop growth model characterizing leaf area index (LAI) dynamics indicated that T2 (40 $g \cdot plant^{-1}$ EM activated calcium + 300 $g \cdot plant^{-1}$ straw) and T6 (40 $g \cdot plant^{-1}$ EM activated calcium + 6 $g \cdot plant^{-1}$ MP3005KM) treatments provided greater LAI growth potential. EM water-retention agents significantly increased net photosynthetic rate (Pn) during the vigorous growth and maturity stages while decreasing transpiration rate (Tr), thereby regulating photosynthesis in tobacco leaves. Principal component analysis revealed that EM water-retention agent application significantly improved the "comprehensive quality" of flue-cured tobacco compared with no application, with straw-based EM water-retention agents showing optimal quality improvement effects. The comprehensive principal component values for T1 and T2 reached 3.25 and 2.76, respectively. Considering factors of "high yield," "good quality," "water saving," and "fertilizer saving," this study recommends an application regime of 40 $g \cdot plant^{-1}$ EM activated calcium combined with 4,500 $kg \cdot hm^{-2}$ straw segments as the optimal EM water-retention agent system. Under this regime, tobacco yield, irrigation water use efficiency, and nitrogen partial productivity reached 2,433.5 $kg \cdot hm^{-2}$, 0.608 $kg \cdot m^{-3}$, and 27.04 $kg \cdot kg^{-1}$, respectively.

Keywords: Effective microorganism (EM); Water-retention agent; Crop straw; Flue-cured tobacco; Application regime

Introduction

Flue-cured tobacco is an important leaf economic crop in China, which has the largest tobacco planting area and total yield worldwide. Tobacco production in southwestern provinces (e.g., Yunnan, Guizhou, Sichuan) plays a crucial role in improving regional economies and fiscal revenues. Currently, the irrigable area in China's tobacco regions reaches 647,300 hectares, but the actual irrigated area is only 420,700 hectares, accounting for approximately 65% of the total irrigable area. Some tobacco regions still rely on natural rainfall, and water infrastructure construction remains relatively underdeveloped. In major tobacco regions such as Guizhou, rainfall is often concentrated during the early and middle growth stages of flue-cured tobacco, while periodic droughts frequently occur during the late growth stage, preventing upper leaves from maturing normally and seriously affecting tobacco quality and usability. Additionally, significant inter-seasonal and inter-annual rainfall variation causes drought stress at different growth stages, resulting in unstable yield and quality. Therefore, strengthening research on water-saving and drought-resistant technologies and improving soil water storage capacity are critical for ensuring high-quality and appropriate-yield production in arid regions.

Water-retention agents can improve soil physical and chemical properties, enhance water retention capacity, improve soil aggregate structure, and increase the availability of soil moisture and nutrients. They have been widely applied in dryland agriculture with promising prospects and have become an important measure for improving rainfall utilization efficiency and alleviating agricultural water pressure. Research by Zhu Yunfeng demonstrated that water-retention agents strongly inhibit soil water evaporation, maintaining soil moisture at relatively high levels for extended periods. Both laboratory and field experiments showed that water-retention agent application reduces soil bulk density while increasing soil porosity and capillary porosity, thereby improving soil permeability and physical structure. Studies by Ding Lin and Zhang Xinmin on the effects of water-retention agents on soil moisture content revealed that both water-retention agent treatments and seed-coating treatments with water-retention agents produced significant water conservation effects, increasing soil water storage by 1.23 mm and 2.25 mm, respectively, compared with pre-sowing conditions. Additionally, numerous reports have documented the yield-promoting effects of water-retention agents on dryland crops.

Effective microorganisms (EM) comprise over 80 species of composite microorganisms across 10 genera, including lactic acid bacteria, yeasts, actinomycetes, and photosynthetic bacteria, characterized by complex composition, stable structure, broad functionality, and non-toxicity. The various microorganisms within EM work synergistically, providing mutual nutrition and progressively decomposing larger animal and plant residues to form symbiotic proliferation relationships. They also inhibit harmful microorganisms by competing for nutrients and space and producing antioxidants. Long-term application of EM alone can coordinate nutrient composition within crops and promote growth and development. Combined application of EM with organic fertilizers can neutralize acidic tobacco-planting soils and improve flue-cured tobacco yield and quality.

However, unified technical standards for water-retention agent application in tobacco cultivation are lacking, and few studies have investigated the mechanisms by which water-retention agents affect tobacco. Research on EM water-retention agents is even rarer. This study used straw segments, MP3005KM water-retention agent, and EM as primary materials to design different EM water-retention agent treatments, exploring the response mechanisms of single-plant leaf area, leaf area index (LAI), photosynthetic indices, yield, and quality to different EM water-retention agents. We aimed to optimize the application regime with maximum comprehensive benefits to provide valuable references for cultivating high-quality and appropriate-yield tobacco in arid regions.

1.1 Experimental Site Overview

The experiment was conducted from May to September in 2014 and 2015 in lysimeters at the Nanjing Institute of Vegetable and Flower Science in Hengxi Town, Jiangning District, Nanjing, Jiangsu Province. The experimental area enjoys abundant sunshine with annual sunshine hours of 2,017.2 h, peaking in August at 215.3 h. The annual evaporation is 1,472.5 mm, with 117 rainy days per year and annual precipitation of 1,106.5 mm. The average annual temperature is 15.7°C, maximum average humidity is 81%, maximum wind speed is 19.8 $m \cdot s^{-1}$, and the frost-free period is 237 days.

The lysimeters were constructed from cement and bricks, each measuring 4 m × 2 m. The soil was backfilled according to natural horizons (bulk density measured) with yellow-brown soil of heavy texture. Soil organic matter content was 14.209 $g \cdot kg^{-1}$, total nitrogen 1.303 $g \cdot kg^{-1}$, available nitrogen 129.9 $mg \cdot kg^{-1}$, total phosphorus 0.363 $g \cdot kg^{-1}$, available phosphorus 27.2 $mg \cdot kg^{-1}$, and pH 5.87. The 0–60 cm soil bulk density was 1.35 $g \cdot cm^{-3}$, and the 0–60 cm field water capacity was 28.0% (gravimetric water content). Groundwater depth was 10 m. Rain shelters were installed above the lysimeters to exclude natural precipitation.

1.2 Experimental Design

The experiment used flue-cured tobacco cultivar 'K326' as the primary material, with 12 plants per lysimeter at row spacing of 1.2 m and plant spacing of 0.5 m. Eight treatments were established: T1 and T2 used air-dried rice straw segments (3–5 cm length) as the primary water-retention material at 4,500 $kg \cdot hm^{-2}$. After complete coverage, EM rejuvenation liquid (T1) or EM activated calcium solution (prepared according to reference [10], T2) was uniformly sprayed on the straw surface around tobacco seedlings. T3 and T4 used EM rejuvenation liquid and MP3005KM water-retention agent as primary materials, where MP3005KM was fully soaked for 24 h before adding EM rejuvenation liquid, mixing evenly, and applying in holes below and beside tobacco seedlings. T5 and T6 used EM activated calcium solution and MP3005KM water-retention agent with the same application method as T3 and T4. Control treatment CK1 applied only 6 $g \cdot plant^{-1}$ MP3005KM water-retention agent, fully soaked for 24 h and applied in holes below and beside seedlings. Control treatment CK2 used no water-retention measures. Specific experimental design and material quantities are shown in Table 1 .

The experiment simulated mild drought stress on flue-cured tobacco with a total irrigation amount of 400 mm. Based on previous research experience [11], irrigation was allocated as 30% during the root extension stage, 40% during the vigorous growth stage, and 30% during the maturity stage. Irrigation was applied every 7 days after transplanting, with the required water amount for each growth stage evenly distributed in the lysimeter soil. Fertilizer was applied as base fertilizer:topdressing = 7:3 using tobacco-specific inorganic fertilizer (provided by Guizhou Tobacco Science Research Institute, $N:P_2O_5:K_2O = 1:2:3$). Base fertilizer was applied in holes before transplanting, and topdressing was applied 30 days after transplanting.

1.3 Measurement Items and Methods

1) Single-plant leaf area and leaf area index (LAI) of flue-cured tobacco

Single-plant leaf area measurement began 14 days after transplanting, with plant height, stem girth, maximum leaf length, and leaf width measured every 7 days. Three plants were selected per treatment. The single-plant leaf area was calculated as follows [12]:

$$A_s = \sum_{i=1}^{n} (L_i \times W_i \times 0.6345)$$

where A_s is the single-plant leaf area (cm^2), n is the number of tobacco leaves, L_i is the maximum leaf length of the ith leaf (cm), and W_i is the maximum leaf width of the ith leaf (cm).

LAI was calculated using the following formula:

$$\mathrm{LAI} = \frac{A_s}{S}$$

where A_s is the total leaf area per plant (cm^2) and S is the ground area occupied by a single plant (cm^2).

A crop growth model proposed by Japanese scholar Qin et al. [13] was used to simulate LAI dynamics:

$$\mathrm{LAI} = \frac{\mathrm{LAI}_M}{1 + \beta e^{-\alpha(t-\tau)}}$$

where LAI is the leaf area index, LAI_M is the theoretical upper limit of LAI, LAI_0 is the theoretical lower limit of LAI, α and β are growth constants, t is days after transplanting, and τ is the number of days required for LAI to reach 1/2 LAI_M. According to model principles, LAI dynamics from 14 to 84 days after transplanting were simulated.

2) Photosynthetic characteristics of flue-cured tobacco

Photosynthetic indices were measured twice during the vigorous growth stage (July 5) and maturity stage (August 10) at 10:30 AM. Three plants were measured per treatment, with the 5th leaf from the top selected for measurement. A LI-6400 portable photosynthesis system (LI-COR, USA) was used with light intensity controlled at 800 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. Measured indices included net photosynthetic rate (Pn), stomatal conductance (Gs), intercellular $\mathrm{CO_2}$ concentration (Ci), and transpiration rate (Tr).

3) Flue-cured tobacco yield

After entering the maturity stage (approximately 84 days after transplanting), leaves were harvested from bottom to top. Tobacco yield was expressed as the mass of cured leaves ($\mathrm{kg \cdot hm^{-2}}$).

4) Flue-cured tobacco quality

Three plants were selected per treatment, and fully mature middle leaves from each plant were cured, dried, ground, and mixed evenly for testing. Chemical components including nicotine, total nitrogen, reducing sugar, and potassium were determined using a continuous flow analyzer with continuous flow methodology [14].

5) Irrigation water use efficiency (IWUE, $\mathrm{kg \cdot m^{-3}}$) [15]

$$\mathrm{IWUE} = \frac{Y}{I}$$

where Y is the dry yield of flue-cured tobacco ($\mathrm{kg \cdot hm^{-2}}$) and I is the total irrigation amount ($\mathrm{m^3 \cdot hm^{-2}}$).

6) Nitrogen partial productivity

Nitrogen partial productivity ($\mathrm{kg \cdot kg^{-1}}$) is the ratio of yield in nitrogen-applied areas to nitrogen application rate [16].

7) Comprehensive principal component of tobacco quality

Tobacco quality comprises numerous indicators with certain interrelationships. For optimizing the EM water-retention regime, this study primarily evaluated "comprehensive quality." Principal component analysis was used to extract main quality components, following the principle of "eigenvalue > 1, cumulative contribution rate $> 80\%$" [17].

1.4 Entropy Weight Coefficient Evaluation Model

The entropy weight coefficient evaluation model is an effective method for high-dimensional data processing. Its advantage lies in the organic combination of subjective and objective weights, considering both decision-makers' subjective experience and original data information, making results more objective and scientific. Based on requirements for "high yield," "good quality," "water saving," and "fertilizer saving," this study selected tobacco yield, quality, irrigation water use efficiency, and nitrogen partial productivity as primary evaluation indices to optimize the EM water-retention agent application regime with maximum comprehensive benefits. The modeling method followed reference [18].

1.5 Data Processing

Significance analysis (Duncan' s multiple range test) and principal component analysis were performed using SPSS 17.0 software.

2.1 Effects of EM Water-Retention Agent on Single-Plant Leaf Area of Flue-Cured Tobacco

As shown in Figure 1 [Figure 1: see original paper], leaf area increased substantially during two stages: 28-42 days and 42-63 days after transplanting, with relatively smaller increases during 63-77 days. At 28 days after transplanting, T6 and T5 treatments showed higher single-plant leaf areas of 2,426.33 cm^2 and 2,380.57 cm^2, respectively, indicating that water-retention agent-based treatments promoted early leaf growth more effectively, while straw segment-based treatments were relatively less effective. During the vigorous growth stage (42-63 days after transplanting), tobacco roots rapidly extended downward and leaves continuously expanded. By 63 days after transplanting, T6 treatment still maintained the largest single-plant leaf area at 22,057.93 cm^2, while CK2 was the lowest at only 16,377.90 cm^2, significantly lower than other treatments. Notably, during 63-77 days after transplanting, T2 treatment showed substantial leaf area growth, reaching the highest level of 25,925.93 cm^2 at 77 days. At this time, T6 treatment had a single-plant leaf area of 25,150.57 cm^2, slightly lower than T2, while CK2 had the smallest leaf area at only 20,309.47 cm^2.

2.2 Effects of EM Water-Retention Agent on LAI of Flue-Cured Tobacco

As shown in Figure 2 [Figure 2: see original paper], LAI changes exhibited three main stages: 14-28 days as a slow growth stage, 28-84 days as a rapid growth stage, and 84-104 days as a decline stage. The LAI decline was primarily due to leaf maturation and the beginning of harvesting. The peak LAI value at 84 days after transplanting is a critical indicator for assessing tobacco growth and yield. Results at 84 days showed that T2 treatment had the highest LAI value of 4.29, followed by T6 at 4.20, which was not substantially different from T2. CK2 had the lowest LAI value at only 3.35. Based solely on LAI values, T2 and T6 treatments performed optimally overall.

Main parameters obtained from the crop growth model simulation are shown in Table 2 . The LAI_M value in the model predicts the theoretical upper limit of LAI for different treatments. In terms of LAI_M values, T2 remained the highest at 4.400, followed by T6 at 4.351, while CK2 was the lowest at only 3.417. This indicates that T2 treatment provided greater growth potential for LAI, whereas CK2 had limited LAI growth potential.

2.3 Effects of EM Water-Retention Agent on Photosynthetic Characteristics of Flue-Cured Tobacco During Vigorous Growth and Maturity Stages

Table 3 shows the effects of different treatments on leaf photosynthetic characteristics during the vigorous growth and maturity stages. During the vigorous growth stage, T2 treatment had the highest Pn at 18.16 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, followed by T6, while CK2 had the lowest Pn at only 14.57 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. Except for control treatments CK1 and CK2, no significant differences in Pn were observed among EM water-retention agent treatments ($P > 0.05$). Compared with the vigorous growth stage, Pn decreased during the maturity stage, with T2 still showing the highest value at 16.10 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$ and CK2 the lowest at 11.76 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. These results demonstrate that EM water-retention agent treatments effectively increased Pn values during both stages, with T2 and T6 showing the most pronounced promotion effects for straw-based and MP3005KM-based treatments, respectively.

During the vigorous growth stage, CK1 treatment had the highest Gs at 0.58 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, followed by T5 at 0.56 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, while T2 had the lowest Gs at only 0.39 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. Gs decreased during the maturity stage, with CK2 showing a relatively high level of 0.33 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, followed by T4 at 0.32 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, and T6 the lowest at only 0.26 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. Based on Gs values from CK1 and CK2 treatments, applying water-retention agent alone had some effect on Gs but the impact was not significant. Among EM water-retention agent treatments, T2 and T6 had lower Gs values for straw-based and MP3005KM-based treatments, respectively.

During the vigorous growth stage, T2 treatment had the highest Ci at 307.30 $\mathrm{mol \cdot mol^{-1}}$, followed by T6 at 301.53 $\mathrm{mol \cdot mol^{-1}}$, with no significant differences among T1, T2, and T6 treatments ($P > 0.05$). CK2 had relatively low Ci during the vigorous growth stage at only 265.20 $\mathrm{mol \cdot mol^{-1}}$. Results from T3-T6 treatments indicated that higher EM rejuvenation liquid and EM activated calcium application rates increased Ci values to some extent, though the increase was not obvious. During the maturity stage, CK1 had higher Ci at 203.27 $\mathrm{mol \cdot mol^{-1}}$, followed by CK2 at 201.68 $\mathrm{mol \cdot mol^{-1}}$, while T1 had the lowest Ci at only 180.80 $\mathrm{mol \cdot mol^{-1}}$. Except for the lower Ci in T1, no significant differences were observed among other treatments during the maturity stage ($P > 0.05$).

During the vigorous growth stage, CK2 treatment had the highest Tr at 3.47 $\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$, significantly higher than other treatments ($P < 0.05$), followed by T3 at 3.20 $\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$, while T6 had the lowest Tr at 2.66 $\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$. Results from T3-T6 treatments demonstrated that increasing EM activated calcium application significantly reduced leaf Tr, while increasing EM rejuvenation liquid had less obvious effects. Tr decreased during the maturity stage, with CK2 still showing the highest value at 2.39 $\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$, significantly higher than other treatments ($P < 0.05$). T2 and T6 treatments maintained lower Tr levels at 1.84 and 1.78 $\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$, respectively.

2.4 Effects of EM Water-Retention Agent on Yield, Quality, IWUE, and Nitrogen Partial Productivity of Flue-Cured Tobacco

As shown in Table 4 , T2 treatment achieved the highest yield at 2,433.5 $\mathrm{kg \cdot hm^{-2}}$, followed by T6 at 2,364.6 $\mathrm{kg \cdot hm^{-2}}$, while CK2 had the lowest yield at only 1,898.1 $kg \cdot hm^{-2}$, significantly lower than other treatments ($P < 0.05$). Compared with controls, all EM water-retention treatments significantly increased tobacco yield ($P < 0.05$), with T3 showing relatively poorer yield improvement.

Nicotine content in all treatments was within the reasonable range (except CK2). Total nitrogen content was high in T3, T5, CK1, and CK2, while other treatments were within the reasonable range. Reducing sugar content was within the reasonable range for all treatments. Potassium content was within the reasonable range except for T2, T4, and T6. Different EM water-retention treatments reduced nicotine and total nitrogen contents while increasing reducing sugar content. However, it is noteworthy that water-retention treatments also reduced potassium content, which may affect leaf combustibility. Differences between EM rejuvenation liquid and EM activated calcium effects on main quality indicators were not substantial, but increasing their application rates reduced nicotine, total nitrogen, and potassium contents in leaves.

Both IWUE and nitrogen partial productivity were highest in T2 treatment, reaching 0.608 $kg \cdot m^{-3}$ and 27.04 $kg \cdot kg^{-1}$, respectively, while CK1 and CK2 controls had lower IWUE and nitrogen partial productivity.

Principal component analysis was applied to extract main components from the quality indicators in Table 4, yielding a cumulative contribution rate of 90.25%, which retained substantial original information. Figure 3 [Figure 3: see original paper] presents the comprehensive principal component values for different treatments, where higher values indicate better "comprehensive quality" and more coordinated chemical composition. T1 treatment showed the optimal "comprehensive quality," followed by T2, while CK2 was the poorest. Overall, straw segment-based EM water-retention treatments produced better tobacco "comprehensive quality" than MP3005KM water-retention agent-based treatments.

2.5 Optimization of EM Water-Retention Agent Application Regime

In the optimization process, selected evaluation indices included tobacco yield, comprehensive quality principal component, IWUE, and nitrogen partial productivity. All four indices were benefit-type indicators. In the entropy weight coefficient evaluation model, subjective weights of 0.3, 0.3, 0.3, and 0.1 were assigned to yield, quality, IWUE, and nitrogen partial productivity, respectively. Objective weights calculated from original data were 0.2406, 0.2405, 0.2782, and 0.2406, respectively, resulting in final comprehensive weights of 0.2866, 0.2866, 0.3313, and 0.0955. The calculated entropy weight coefficient evaluation values for T1-CK2 were 0.9470, 0.9497, 0.8421, 0.8214, 0.8471, 0.8866, 0.7986, and 0.6237, respectively, indicating that T2 was the optimal EM water-retention agent application regime.

3 Discussion and Conclusions

Except for T3, all EM water-retention agent treatments significantly promoted single-plant leaf area growth, demonstrating that reasonable EM water-retention agent formulations can effectively increase fresh tobacco yield. Meanwhile, EM water-retention agent treatments also improved tobacco yield, consistent with results from studies by Lu Yaofan et al. and Wang Yuping et al. using straw and polymer resin as primary water-retention materials. Notably, during the middle and late growth stages, straw-based EM water-retention treatments showed the greatest increase in single-plant leaf area, possibly because nutrients in straw were gradually released with increased irrigation frequency and effective microbial activity, supplementing tobacco nutrient supply to some extent. Research by Wang Meixin et al. indicated that EM application can increase soil available nutrient content.

In previous studies, we reported LAI simulation models for flue-cured tobacco, including cosine models, universal models, linear models, and exponential models. These models primarily simulated LAI changes based on curve patterns, yielding parameters with limited significance. In contrast, the crop growth model introduced in this study provides parameters with good predictive value for tobacco growth and yield, demonstrating strong application potential.

Regarding quality effects, straw showed superior "quality improvement" effects compared with MP3005KM water-retention agent. Research by Zuo Guangling et al. demonstrated that applying straw-based water-retention agents increased average soil moisture content by 3.1% compared with controls, increased tobacco yield by 18.4%, and improved premium leaf proportion by 6.8%. In this experiment, differences in quality effects between straw-based and MP3005KM-based water-retention treatments may primarily stem from different water-retention mechanisms: MP3005KM water-retention agent forms a local "mini reservoir" around tobacco roots to supply water, whereas straw segments uniformly cover the soil surface, physically isolating soil from the external environment and reducing soil surface evaporation. Visually, soil under straw cover remained moist for longer periods, while MP3005KM water-retention agent only ensured local soil moisture, and once exposed to the surface, absorbed water evaporated rapidly. Overall, straw provided better water-retention effects, ultimately reflected in superior tobacco quality.

Regarding photosynthesis, the promotion of Pn by EM water-retention agents may result from increased water supply to tobacco plants and improved nitrogen nutrient availability from fertilizer due to water-retention agent application. Zhao Mingqin et al. suggested that water-retention agents primarily affect Pn by regulating Gs in tobacco leaves. Overall, EM activated calcium was more effective than EM rejuvenation liquid in reducing Gs, possibly due to Ca^{2+} effects. Studies have shown that Ca^{2+} plays an important role in controlling cell and tissue development, promoting tobacco growth, and improving drought resistance. Higher Ci values during the vigorous growth stage in EM water-retention agent treatments compared with controls may be because EM water-retention agents reduced Gs, resulting in slight intercellular CO_2 surplus when CO_2 concentration entering intercellular spaces remained unchanged and synthesis capacity was limited. Additionally, both water-retention agent alone and EM water-retention agent treatments reduced Tr, confirming and supplementing the findings of Xu Zhiqiang et al.

Entropy weight coefficient evaluation model results indicated T2 as the optimal EM water-retention agent application regime, demonstrating that T2 provided the best comprehensive benefits in terms of "high yield," "good quality," "water saving," and "fertilizer saving." Although T6 performed well in "high yield," "water saving," and "fertilizer saving," its relatively poor comprehensive leaf quality reduced its entropy weight coefficient evaluation value. Compared with other optimization models such as projection pursuit classification, the entropy weight coefficient evaluation model combines subjective and objective weights, following original data information while considering decision-makers' subjective experience, making optimization results more reliable and scientific. Notably, this study transformed four tobacco quality indicators into a "comprehensive quality principal component" for entropy weight coefficient evaluation model calculation, effectively avoiding unreasonable weight distribution caused by too many quality sub-indices. This study selected yield and quality indices to evaluate EM water-retention agent effects but did not include soil and root indices such as soil moisture content and tobacco root system activity, which warrant further investigation.

Given the wide distribution of tobacco-planting regions and diverse soil types in China, appropriate water-retention agent application rates and preparation methods must vary under different soil drought conditions. Therefore, before determining water-retention agent rates, targeted "bare soil evaporation" experiments could be conducted—measuring daily evaporation under different water-retention agent treatments without tobacco planting—to provide a basis for designing application rates. This study was conducted in Nanjing, where climate conditions differ somewhat from major drought-prone tobacco regions; thus, relevant parameters in these results should be appropriately adjusted for practical application. While numerous reports have addressed straw and water-retention agent application methods in tobacco cultivation, research on EM usage techniques and methods needs strengthening. EM water-retention agent development should focus on "high yield, good quality, water saving" and "environmentally friendly" directions. Additionally, due to high EM costs, expansion cultivation is often required before application, and solving coordination and symbiosis issues among microbial flora during expansion cultivation is also key to research. In this study, the cost of straw-based EM water-retention agent was approximately 0.14-0.18 $\text{yuan} \cdot \text{plant}^{-1}$, while MP3005KM-based EM water-retention agent cost about 0.42-0.50 $\text{yuan} \cdot \text{plant}^{-1}$.

In conclusion, EM water-retention agent treatments benefit tobacco growth and development while improving yield and quality. The regime of 40 $\text{g} \cdot \text{plant}^{-1}$ EM activated calcium combined with 4,500 kg · hm^{-2} straw segments provides optimal comprehensive benefits, increasing single-plant leaf area, LAI, and LAI_M values, enhancing Pn during vigorous growth and maturity stages while reducing Tr, and improving tobacco "comprehensive quality." This study recommends 40 g · $plant^{-1}$ EM activated calcium combined with 4,500 kg · hm^{-2} straw segments as the optimal EM water-retention agent application regime.

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